Effect of Mechanical Stress on Gate Current and Degradation in AlGaN/GaN HEMTs

Amit Gupta, Mehmet Baykan, Robert Dieme, Varun Khandelwal,
Scott Thompson, and Toshikazu Nishida

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Gator Engineering
University of Florida

Outline

- Motivation
- Gate Leakage Stress Dependence in AlGaN/GaN Schottky Diode
- Photoionization Spectroscopy – Trap Characterization
- Understanding Degradation Mechanisms in GaN HEMT
- Design of AlGaN/GaN HEMT Test Structures and Layout
- Summary and Future Work

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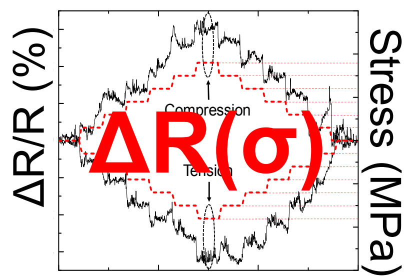
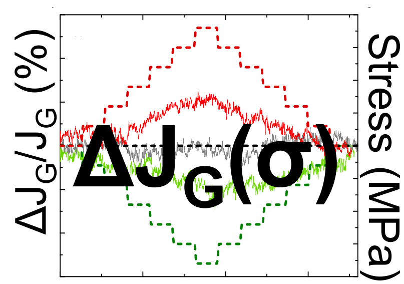
Mechanical Stress on GaN HEMT Reliability

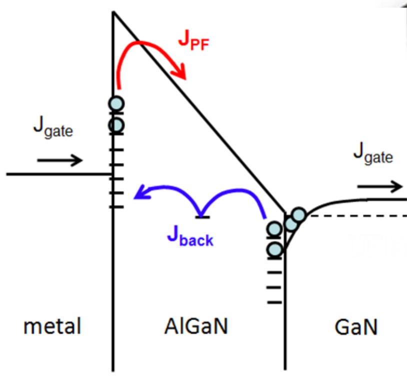
FLOORS

Stress Measurements

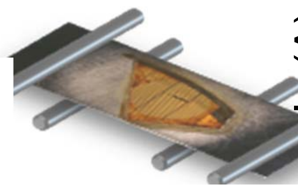




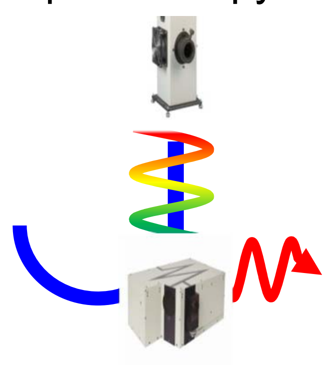
Gate Leakage Modeling



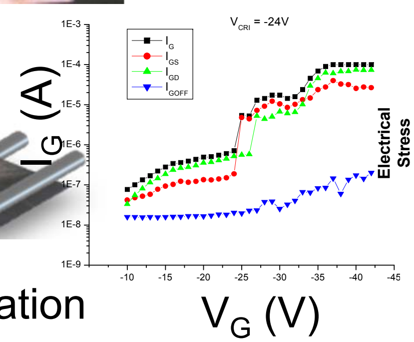
Wafer Bending

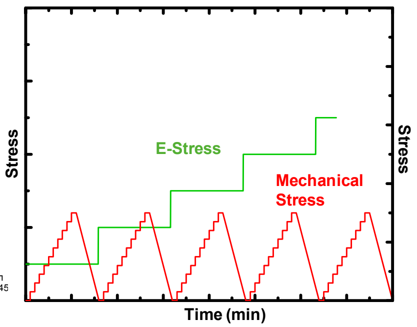


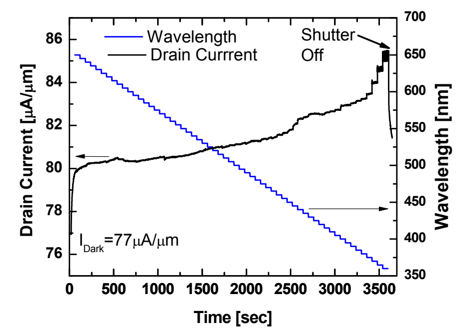
Photoionization Spectroscopy



Stress Measurements







t=0, As Built

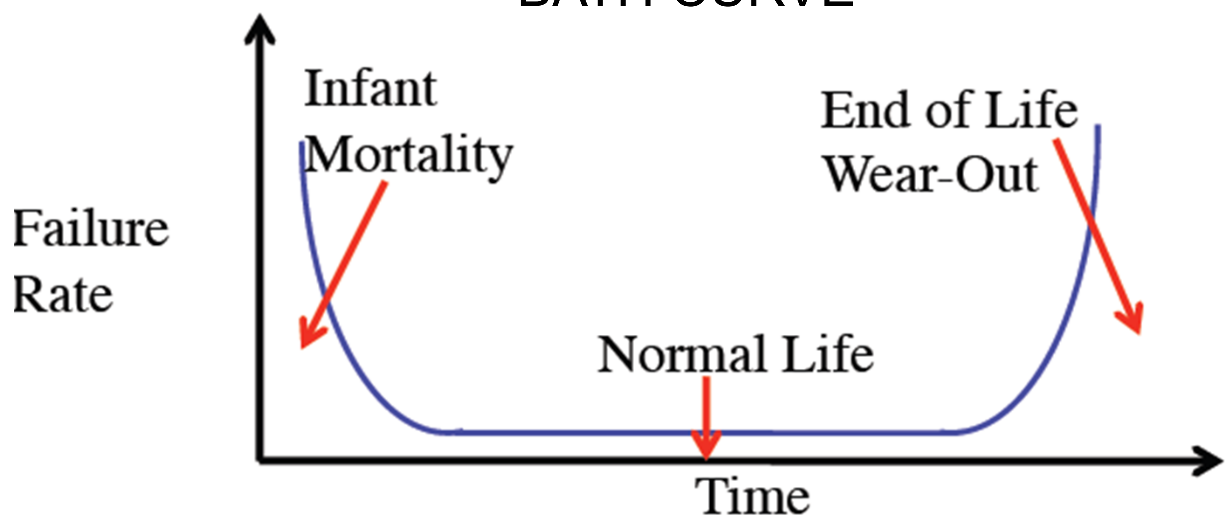
t>0, Degradation

Motivation

- MTTF > 10^6 hours at 200°C
  > 10^7 hours at lower temperatures [1]
- Understand fundamental mechanism causing electrical device degradation

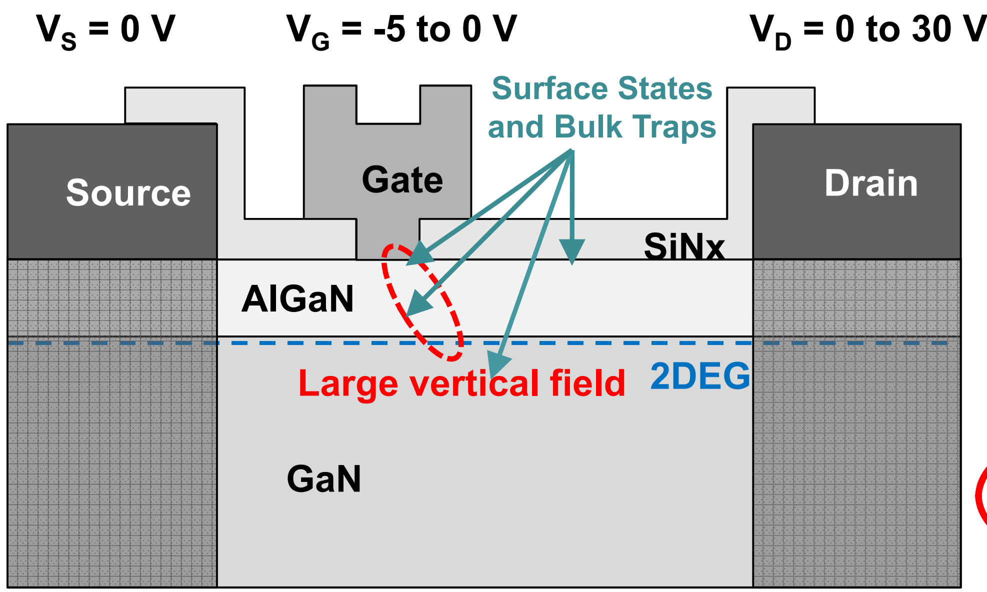
- Reduce early failures and increase device life time

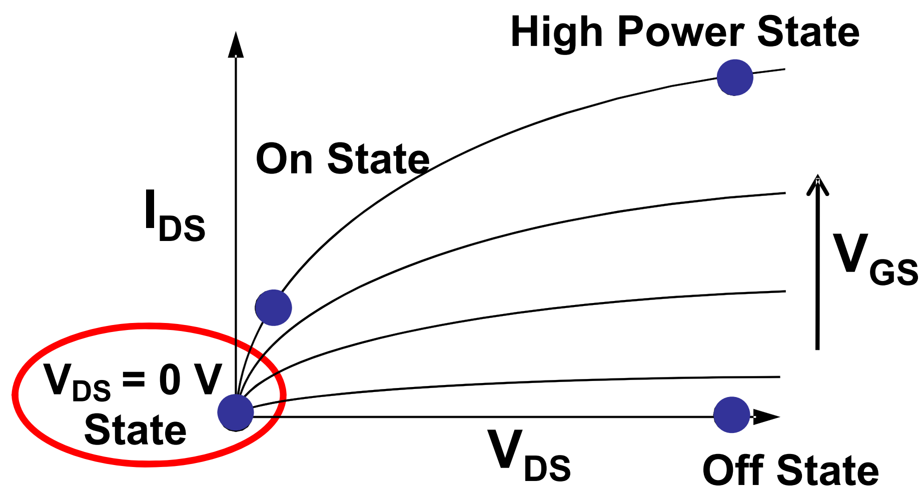
BATH CURVE



1. S. Singhal, T. Li, A. Chaudhari, K. J. Linthicum, et. al., "Reliability of large periphery GaN-on-Si HFETs," Proc. Reliab. Compound Semicond. Workshop (ROCS), pp. 135-149, 2005.

Stress on GaN HEMT IG Degradation





- Large vertical field induces additive stress, drives charge transport, and is one factor affecting degradation.
- Investigate mechanical stress effect on gate leakage, at varying gate biases, at V_{DS}= 0V state (isolate effect of vertical field).

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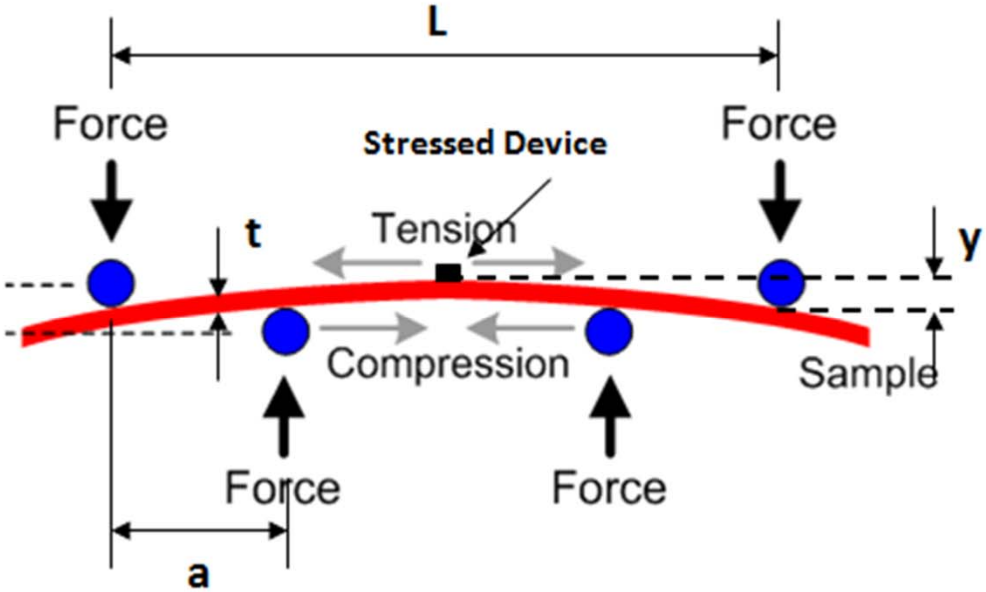
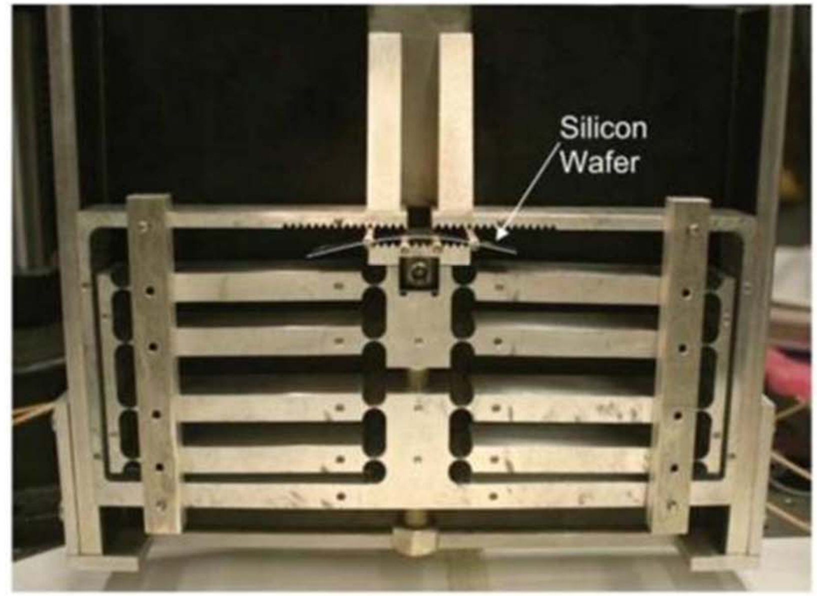
4-point Wafer Bending



Flexure-based Wafer Bending



Stress on upper surface at center of the substrate

$$\sigma = \frac{E \cdot t \cdot y_{x=a}}{2a\left(\frac{L}{2} - \frac{2a}{3}\right)}$$

E = Young's modulus
t = sample thickness
y = vertical displacement
a, L = rod spacing

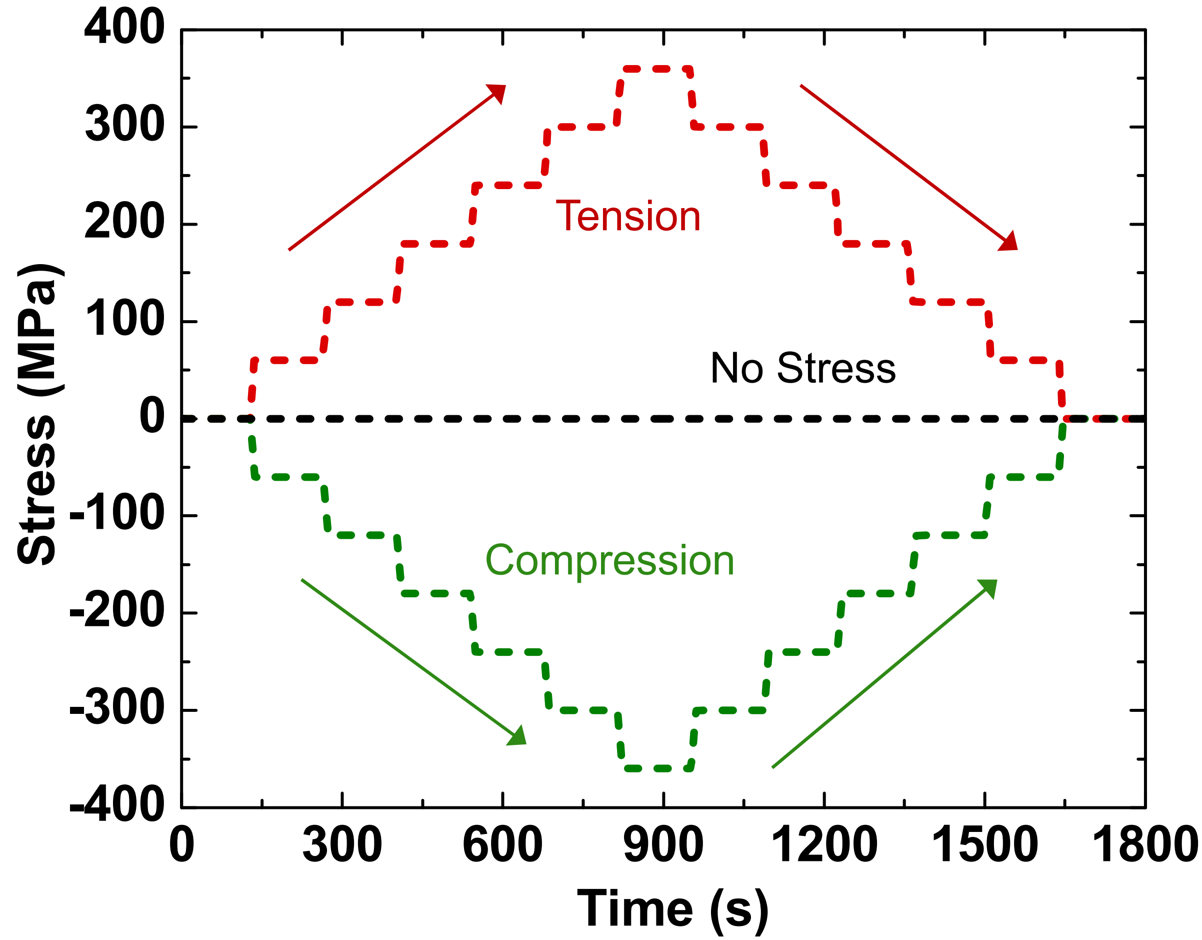
[*Strength of Materials, edited by S. Timoshenko Krieger, Melbourne, FL,*1976]

Stress Dependence of J_G Procedure

Stabilization
- Bias device in dark & measure I_G at V_{DS}=0V
- Wait till JG stabilizes

Stressing
- Apply / Release stress incrementally

Analysis
- Average J_G over each stress and estimate $\Delta J_G/J_G$



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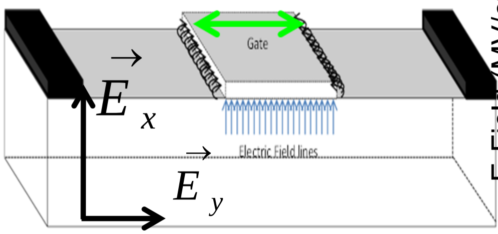
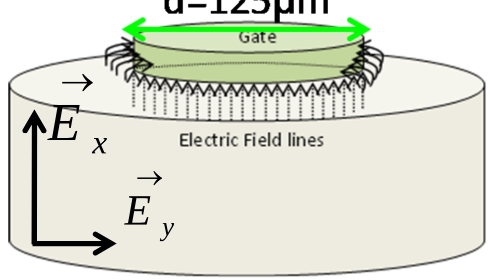
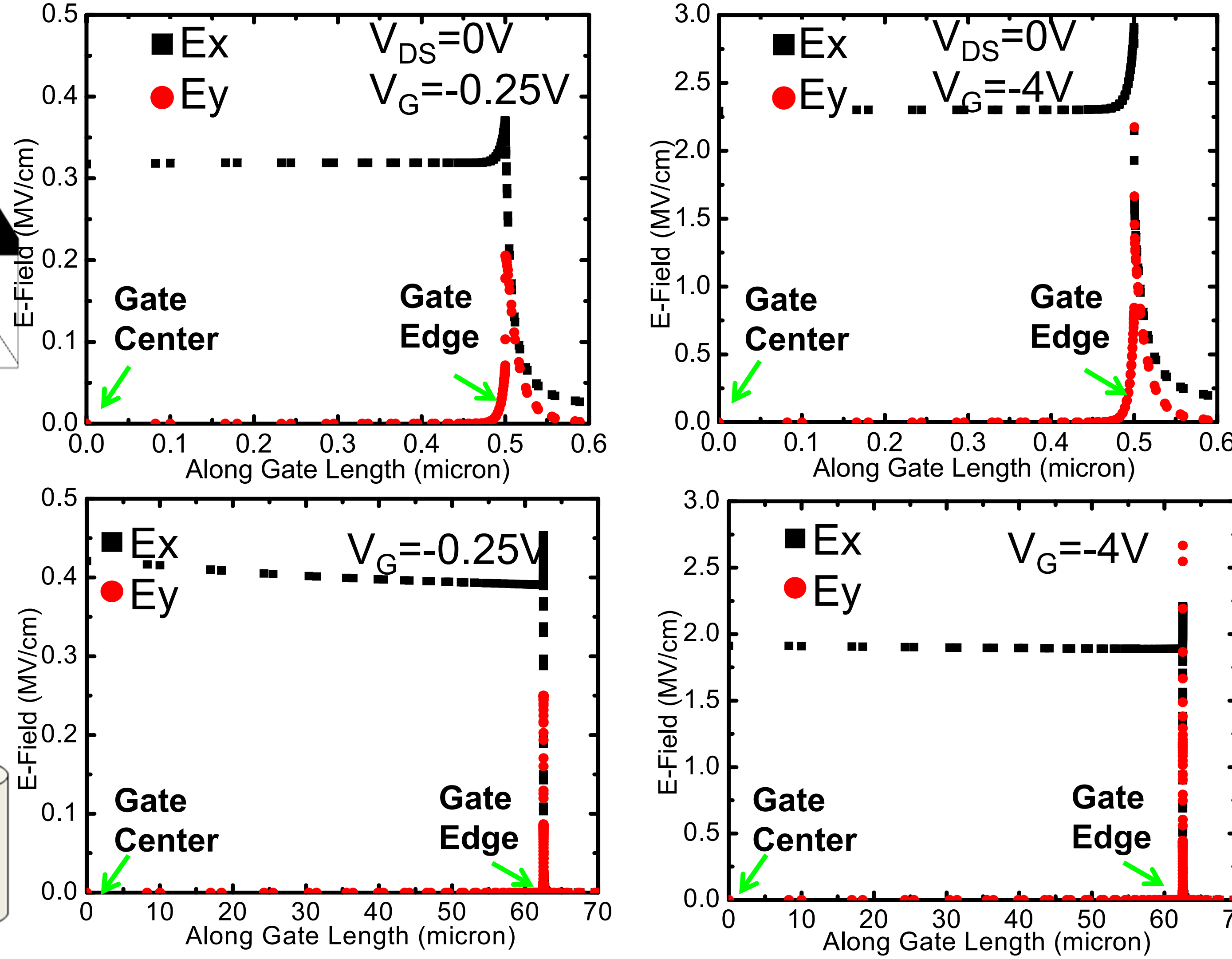
E-Field in GaN HEMT and Schottky Diode

AlGaN/GaN
HEMT



AlGaN/GaN
Schottky diode

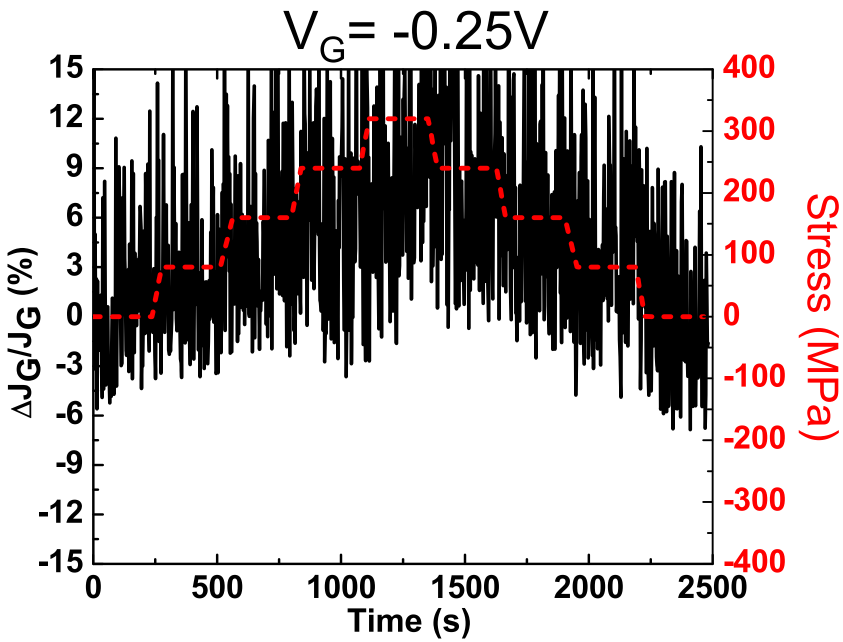


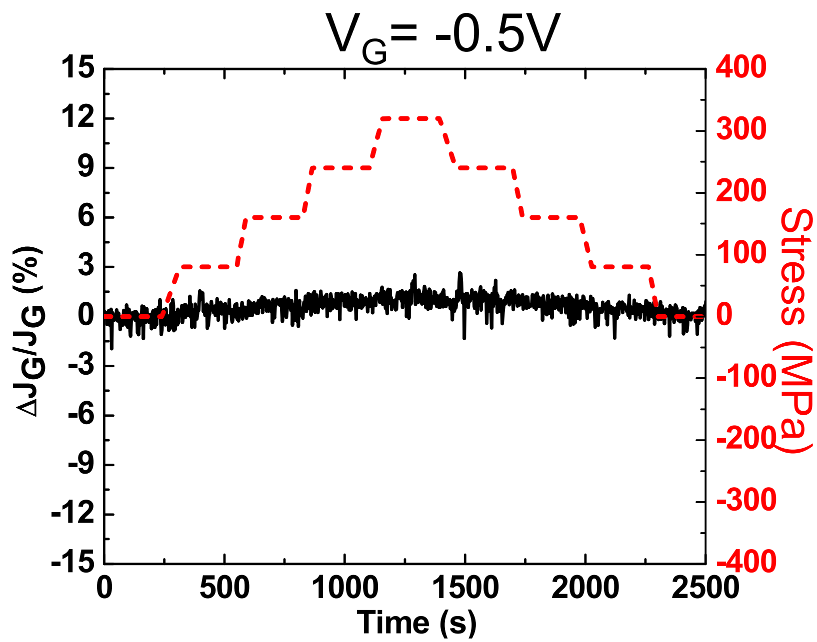


Courtsey: Erin Patrick, Dr. M. Law

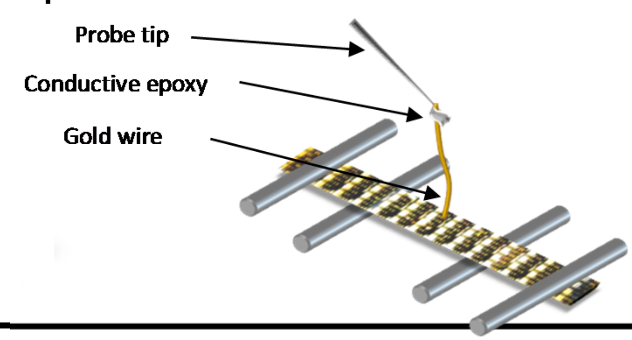
I_G vs Stress (Schottky Diode)

AFRL sample on SiC substrate



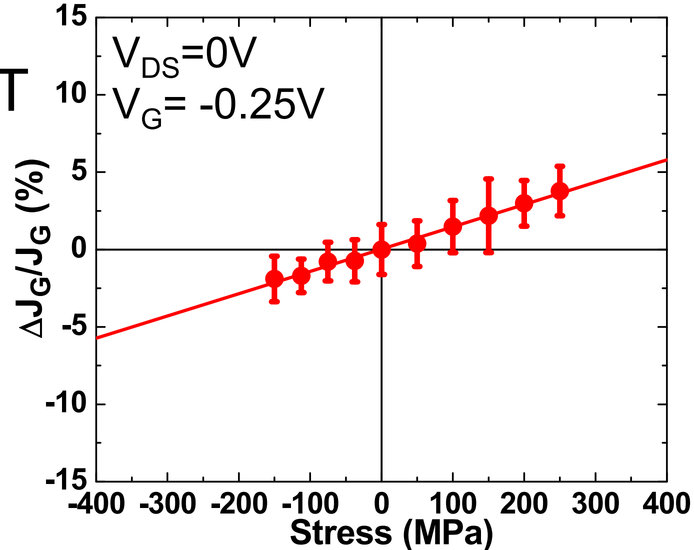


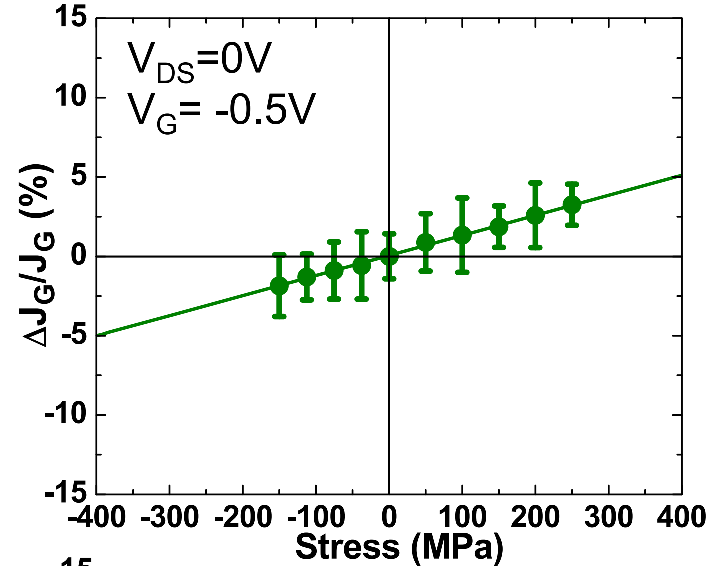
- Longitudinal tensile stress is incrementally applied up to 320 MPa and then released
- As tension is increased, I_G increases
- I_G measured is more noisy at lower bias



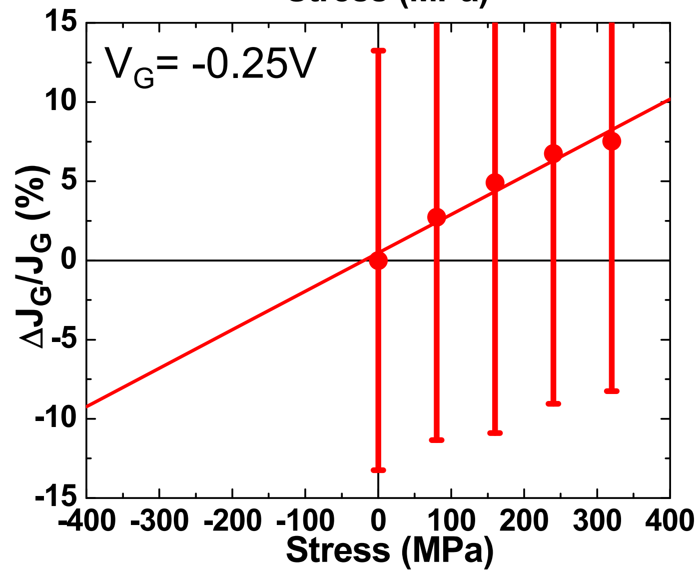
Stress Dependence of HEMT and Schottky Diode

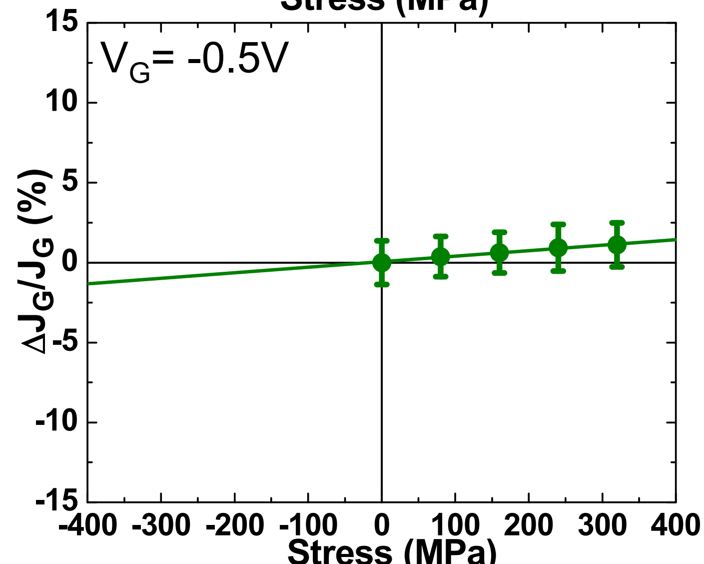
AlGaN/GaN HEMT on SiC substrate





AlGaN/GaN Schottky diode on SiC substrate





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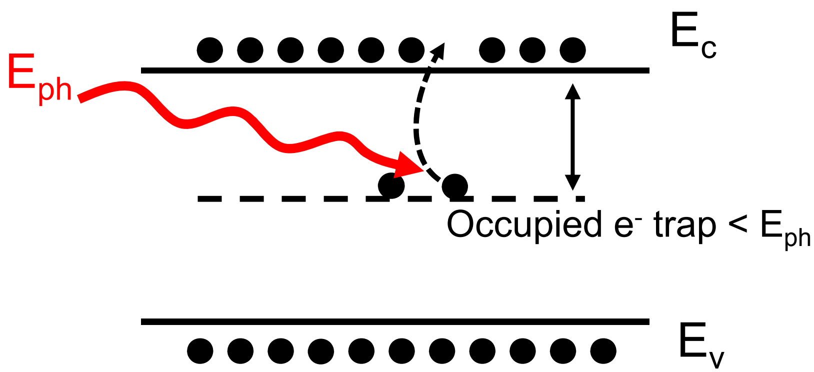
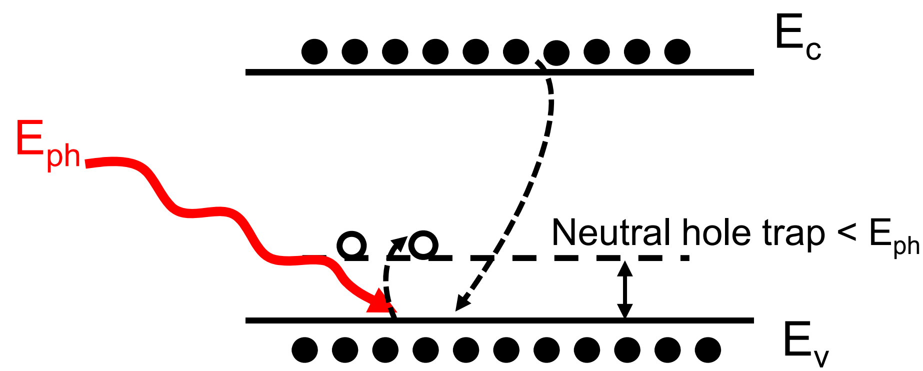
Photoionization Spectroscopy

Current increase:



Current decrease:



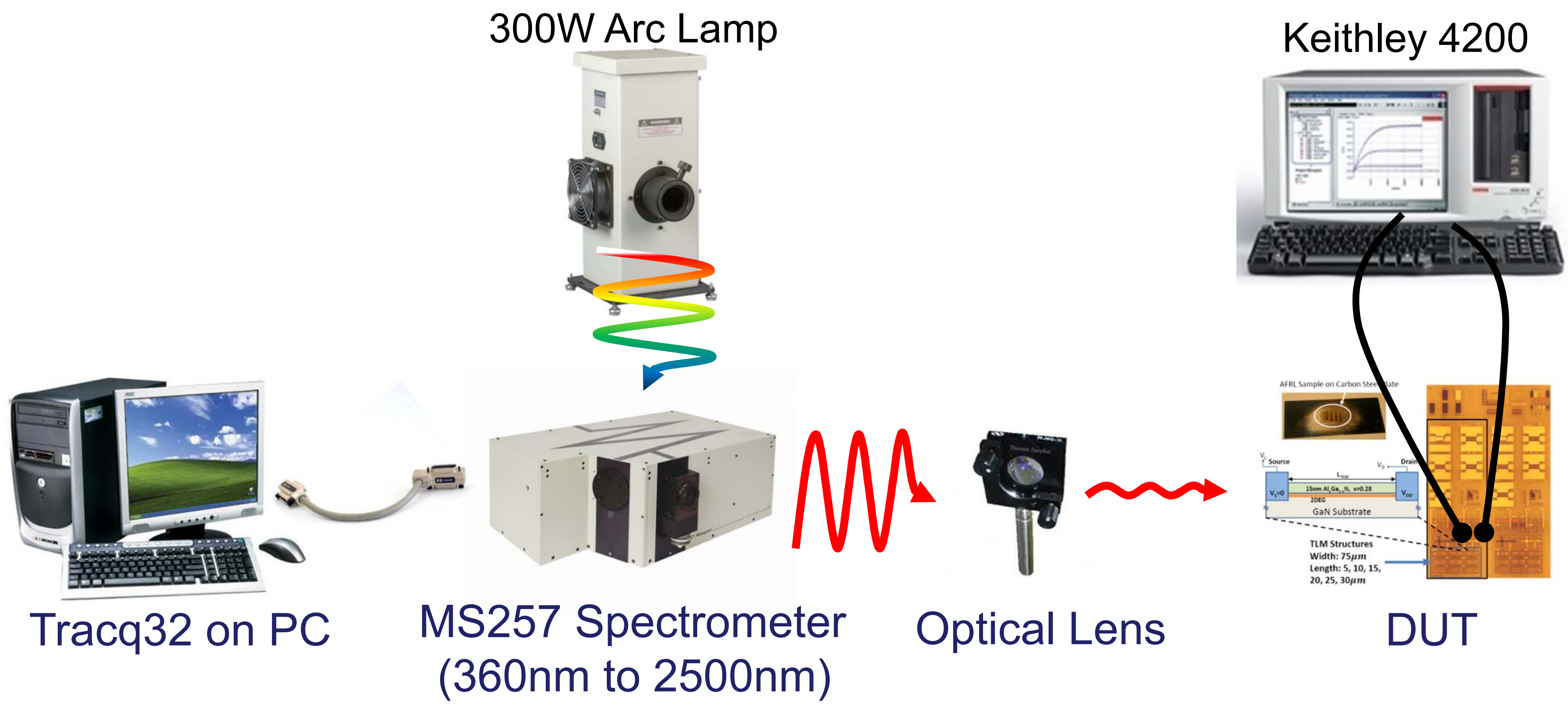
- Can characterize both electron and hole trap density [2]
  - Assumes near-steady state saturation of drain current for each photon energy

$$\frac{D_{it}(h\nu_f)}{N_{2DEG}} \cong \frac{I(h\nu_f) - I(h\nu_i)}{I_{Dark}}$$

D_{it} : areal interface trap density
I : Drain current
N_{2DEG}=Sheet charge density

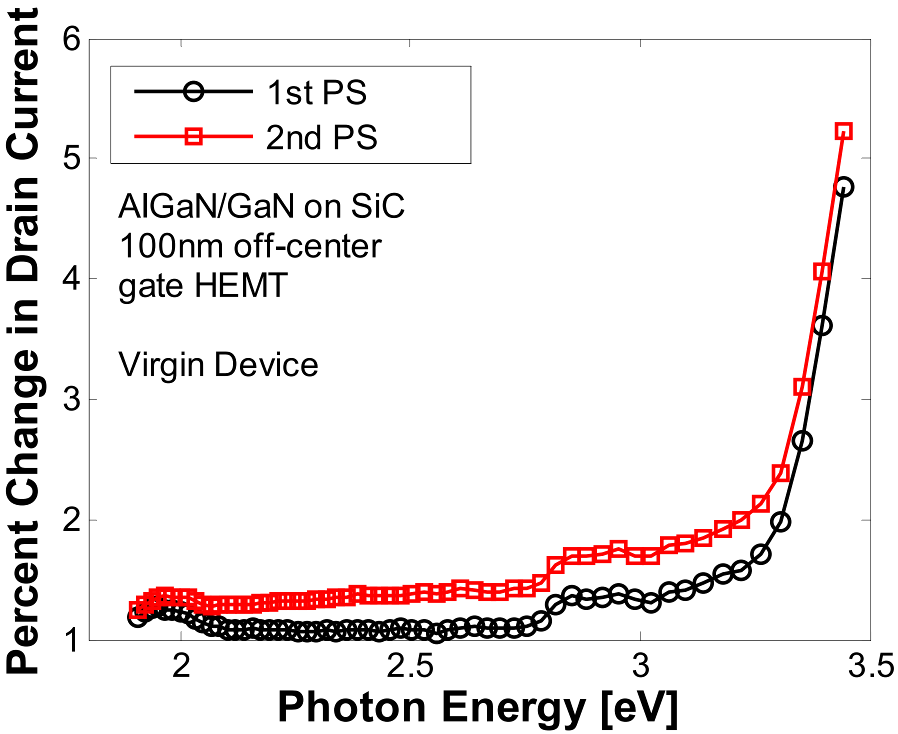
2. P. B. Klein and S. C. Binary, " Photoionization spectroscopy of deep defects responsible for current collapse in nitride-based field effect transistors", J. Physics: Condensed Matter, 15, 1641-67, 2003

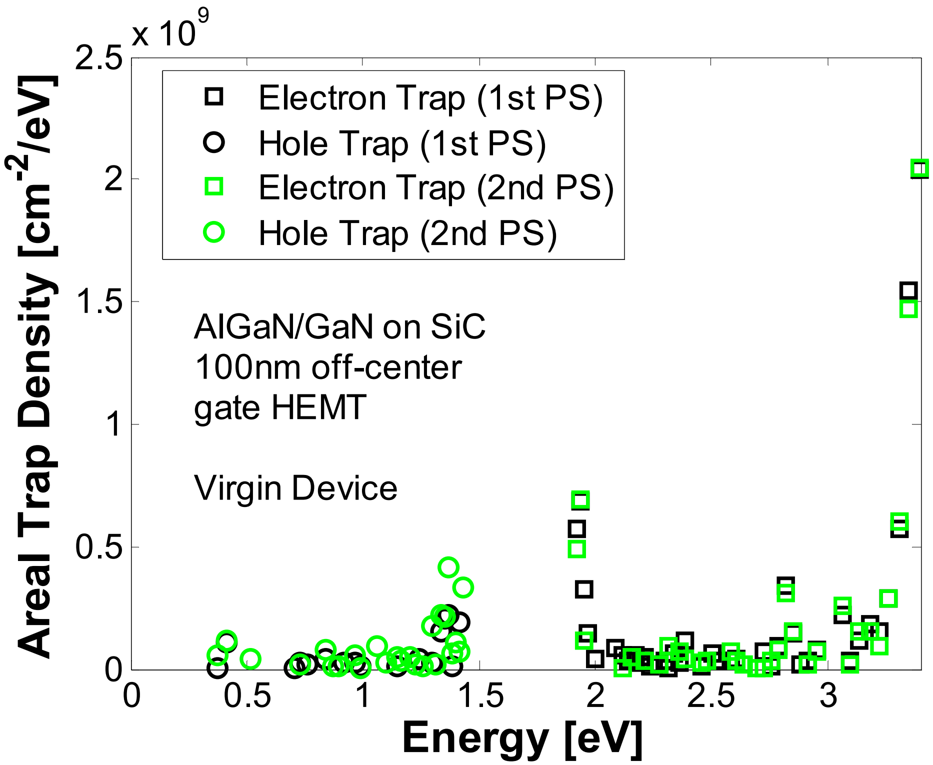
Photoionization Spectroscopy Set up



- Higher-order filter is used to cut-off higher order illumination from Red-to-near-IR spectrum
- Light is routed with mirrors and lenses to reduce transmission losses

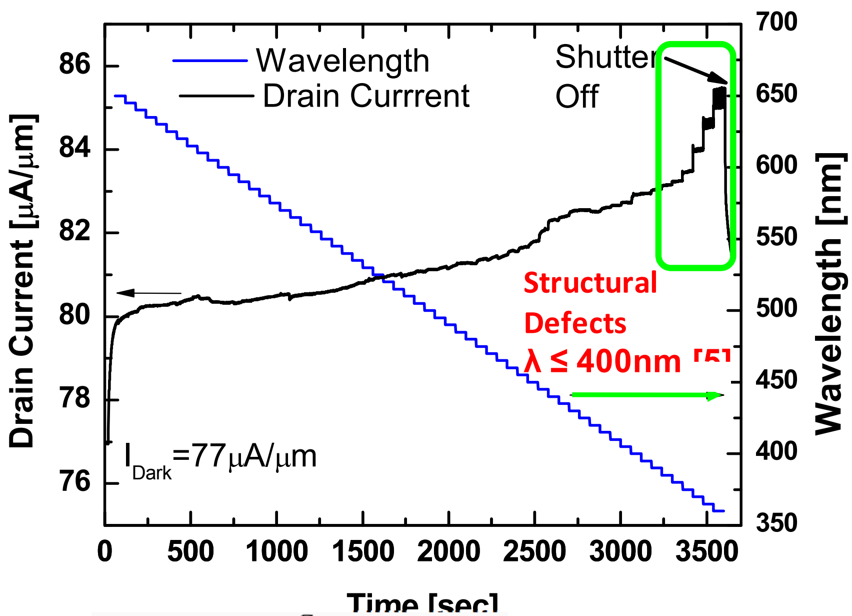
Repeatability of Trap Characterization using PS

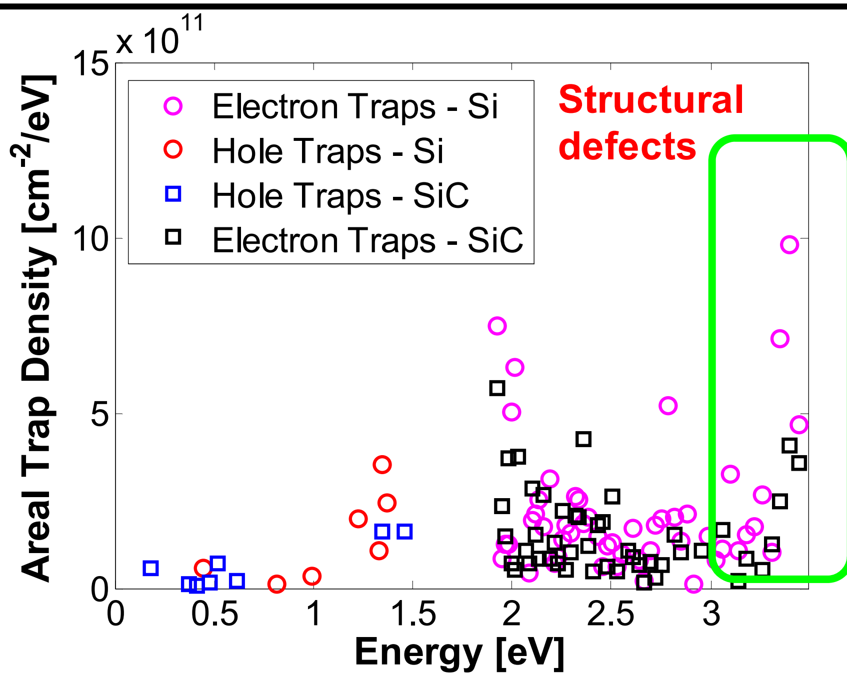


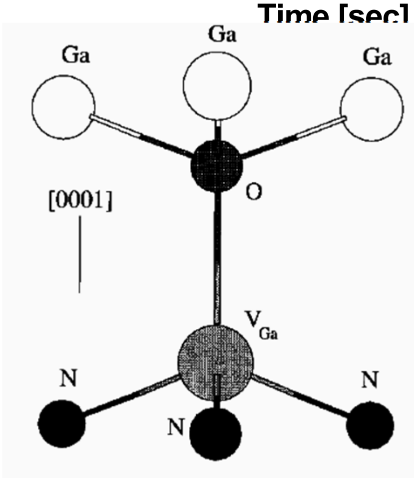


- 2 consecutive PS measurement repeated on virgin device
  - Device kept in dark for 30 minutes after the 1st PS experiment
  - Error in percent change in linear I_D is around 0.5%

Trap Characteristics of HEMT on Si vs SiC







- HEMTs on Si substrate exhibit larger sensitivity to near bandgap photons compared to HEMTs on SiC substrate
- Near bandgap defects ascribed to GaN structural defects [3, 4]

[3] R. Liu et al., Appl. Phys. Lett. 86, 021908, 2005.
[4] M. Haugk et. al., Phys. Stat. Sol. (b) 217, 473, 2000.

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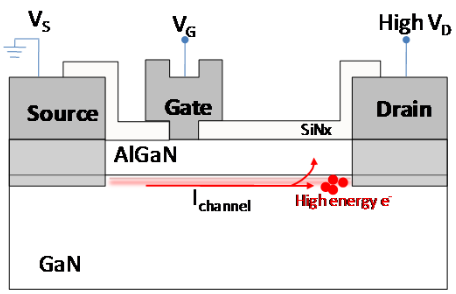
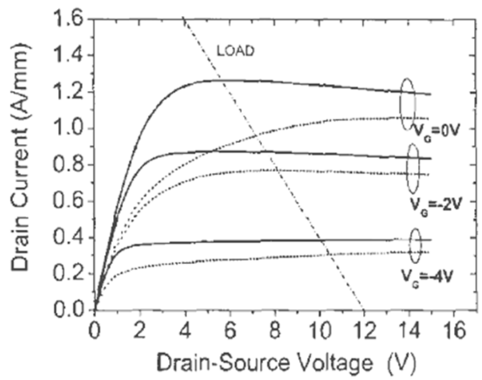
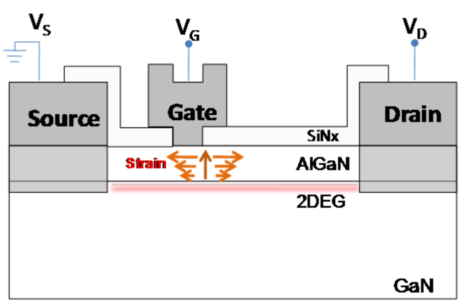
Failure Mechanisms in GaN HEMTs

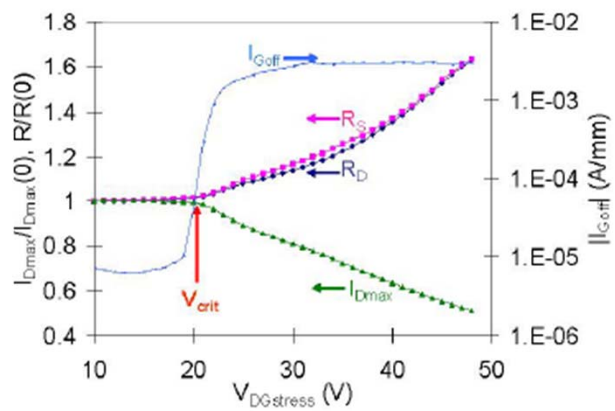
Hot e-Injection and Trapping [5]





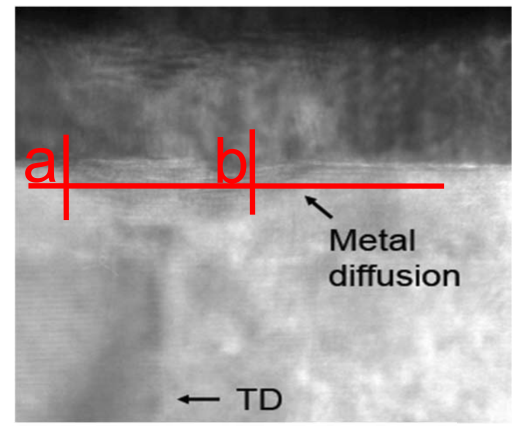
Strain due to Inverse Piezoelectric Effect & Lattice Mismatch [6]

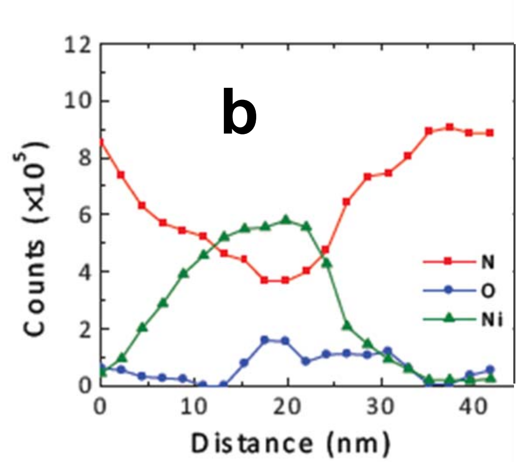




5. Meneghesso G,et al., IEEE Proc Int Rel Phys Symp,415–22, 2005
6. J Joh et. al., IEEE IEDM,385-388,2007

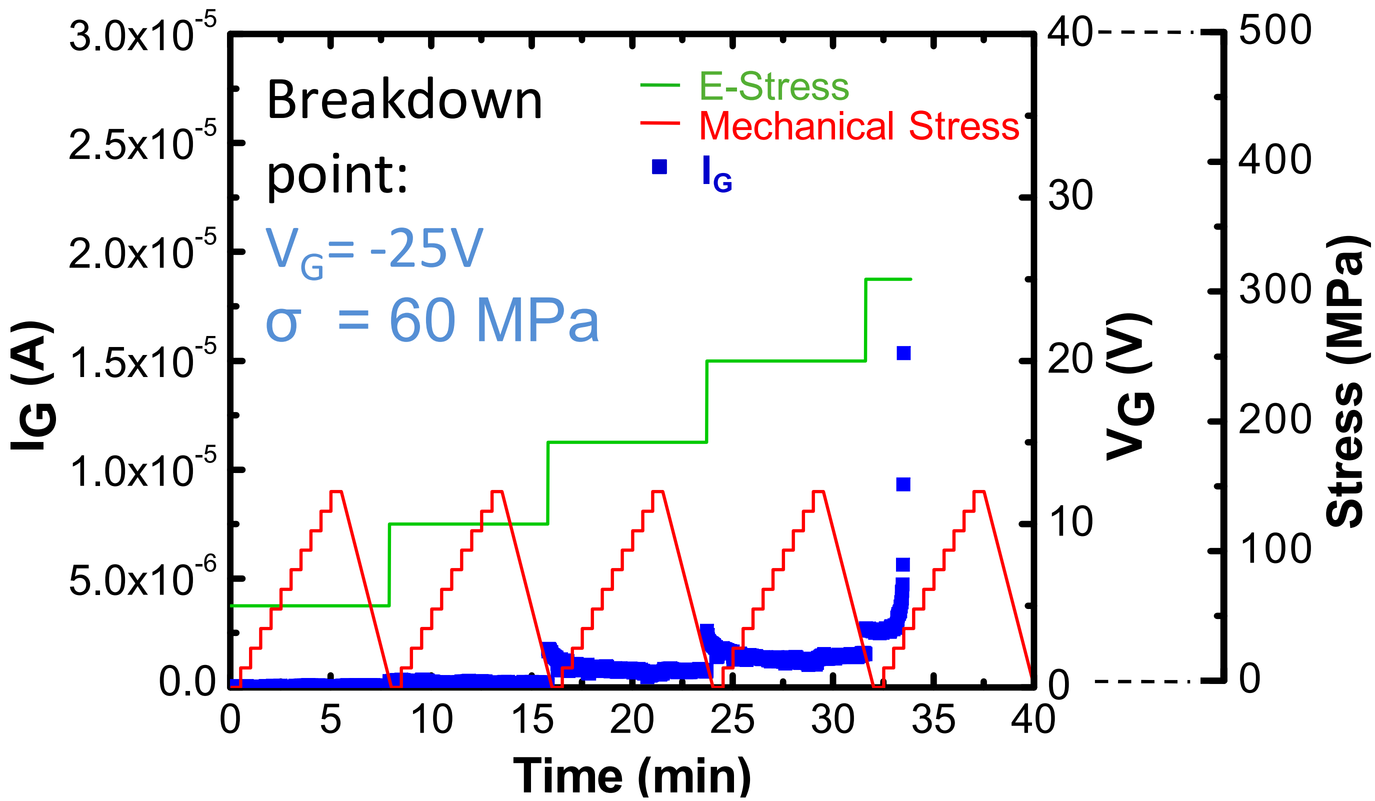
Metal Diffusion & Chemical Reaction [7]





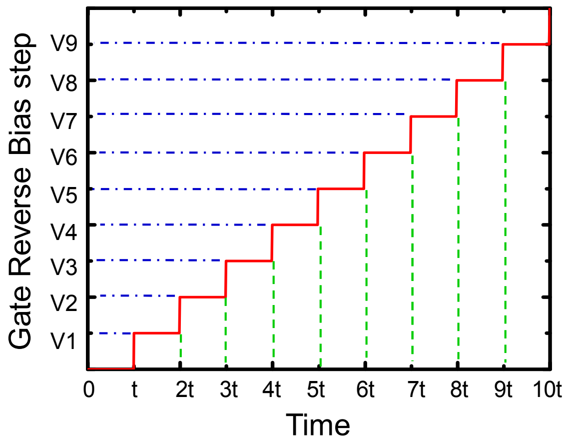
7. L. Liu, et al., J. Vac. Sci. Technol. B 29, 032204, 2011

I_G Degradation under Electrical-Mechanical Stress



- V_G step size is -5V, each step applied for 8min
- Uniaxial tensile stress applied in steps of 15 MPa upto150 MPa
- Measure I_G during the application of stress

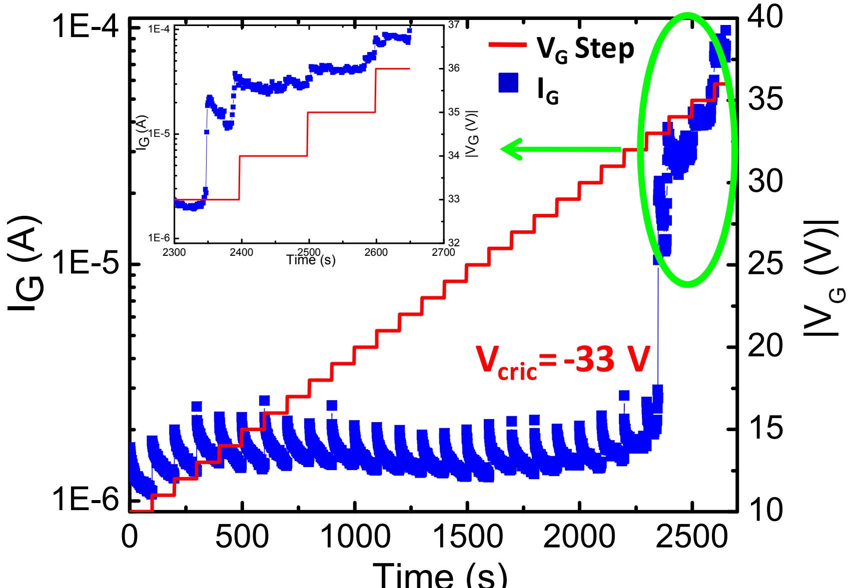
Time Dependent Electrical Step Stress



- Length 't' of each E-stress step is varied: t=10sec, 100sec, 500sec, 1000sec
- Trapping transients are observed at each stress step prior to breakdown
- One large sudden increase in I_G is observed, followed by multiple small jumps in I_G

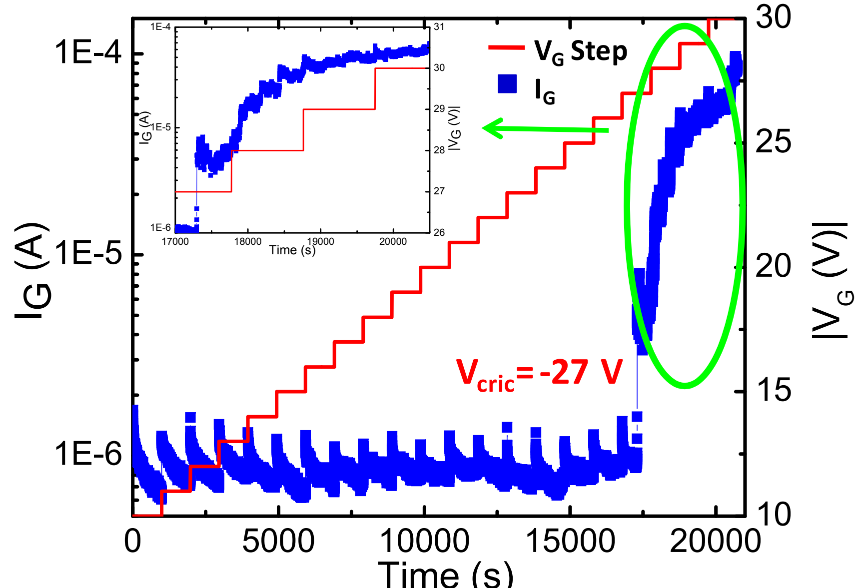
DEVICE A

V_{DS} = 0V, 100 sec/step



DEVICE B

V_{DS} = 0V, 1000 sec/step



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Strain Relaxation in Heterostructures

Pressure effects on self-diffusion in silicon

A. Antonelli and J. Bernholc
Department of Physics, North Carolina State University, Raleigh, North Carolina 27695-8202
(Received 17 March 1989; revised manuscript received 7 September 1989)

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Thermal relaxation of pseudomorphic Si-Ge superlattices by enhanced diffusion and dislocation multiplication

S. S. Iyer and F. K. LeGoues
IBM Research Division, T. J. Watson Research Center, PO Box 218, Yorktown Heights, New York 10598

(Received 21 October 1988; accepted for publication 5 February 1989)

Pseudomorphic Si/Si-Ge strained layer superlattices are metastable and will relax to lower-

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Dependence of boron cluster dissolution on the annealing ambient

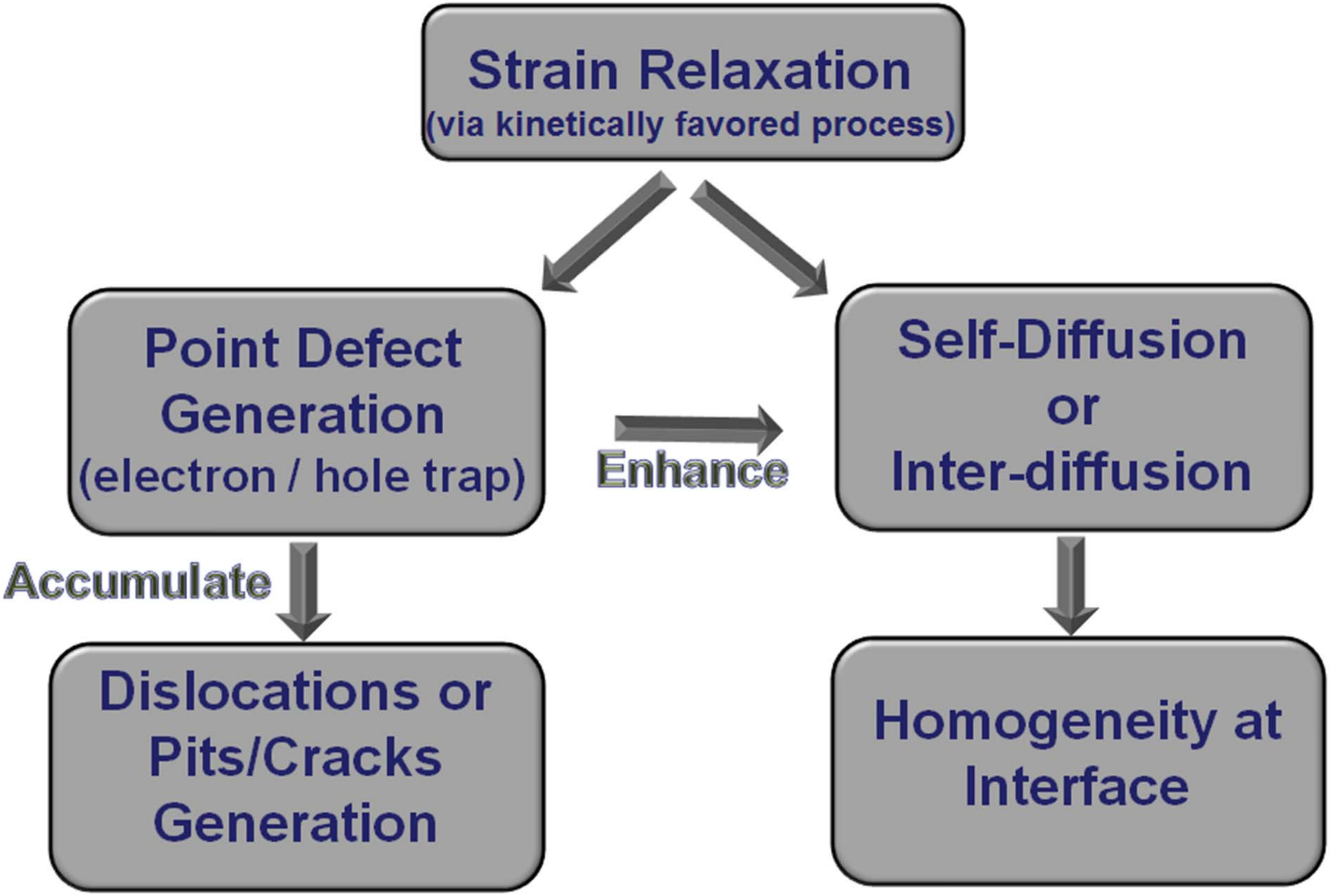
Ljubo Radic,[a] Aaron D. Lilak, and Mark E. Law
SWAMP Center, University of Florida, Gainesville, Florida 32611

(Received 12 April 2002; accepted for publication 30 May 2002)

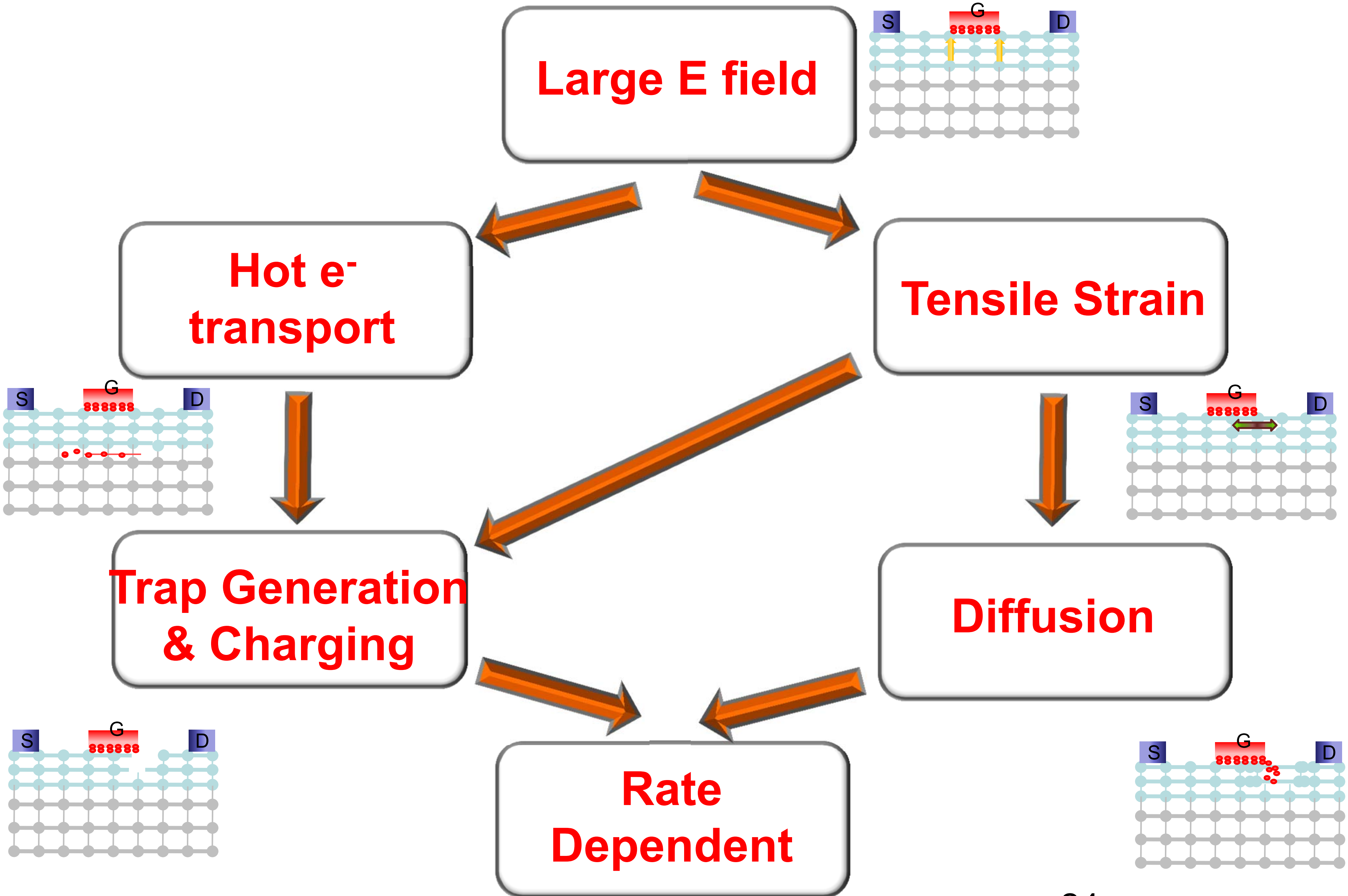
Boron is introduced into silicon via implantation to form *p*-type layers. This process creates damage in the crystal that upon annealing causes enhanced diffusion and clustering of the boron layer. Reactivation of the boron is not a well-understood process. In this letter we experimentally investigate the effect of the annealing ambient on boron reactivation kinetics. An oxidizing ambient which injects silicon interstitials is compared to an inert ambient. Contrary to published theory, an excess of interstitials does not accelerate the reactivation process. © *2002 American Institute of Physics*. [DOI: 10.1063/1.1496505]

Ion implantation is the preferred method of introducing dopants due to the precision of the implanted dose, control and repeatability. Future technology nodes will require used to determine the influence of annealing ambient on cluster formation or dissolution. Clustering effects are investigated via SIMS and Hall effect measurements.

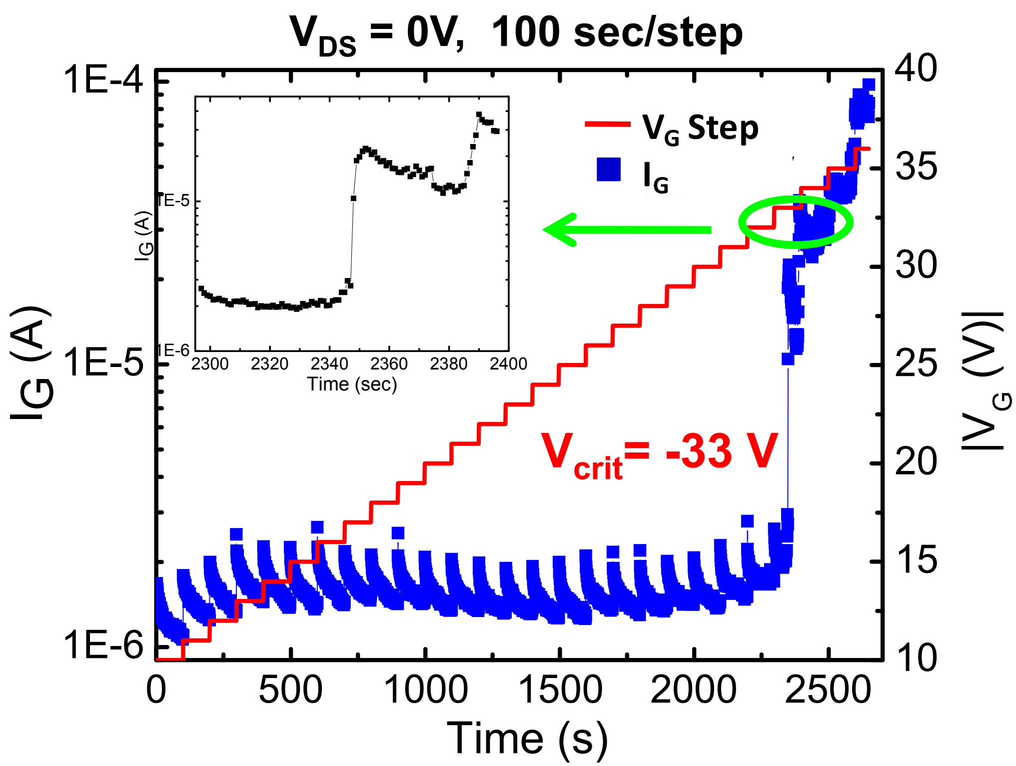
Strain Relaxation Process

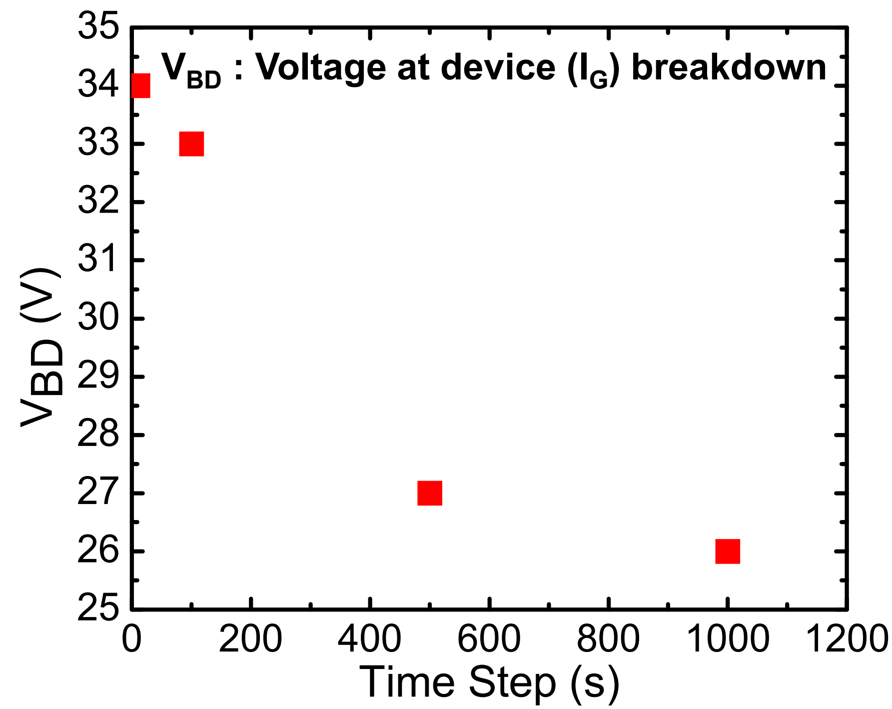


Strain Relaxation in GaN HEMT



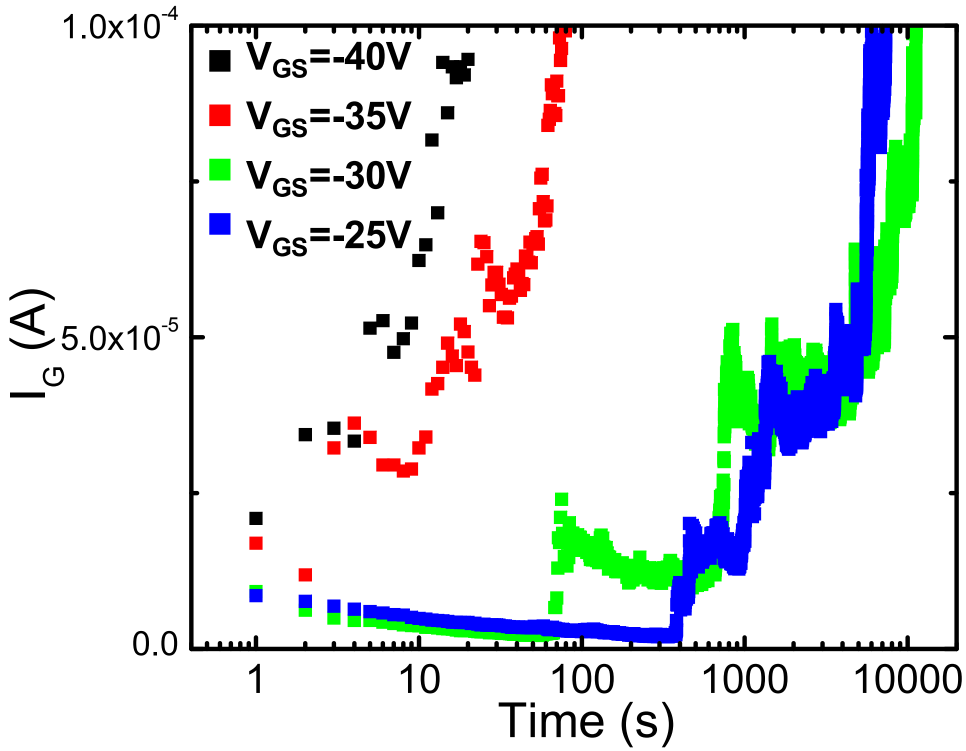
Time Dependent I_G Degradation in GaN HEMT

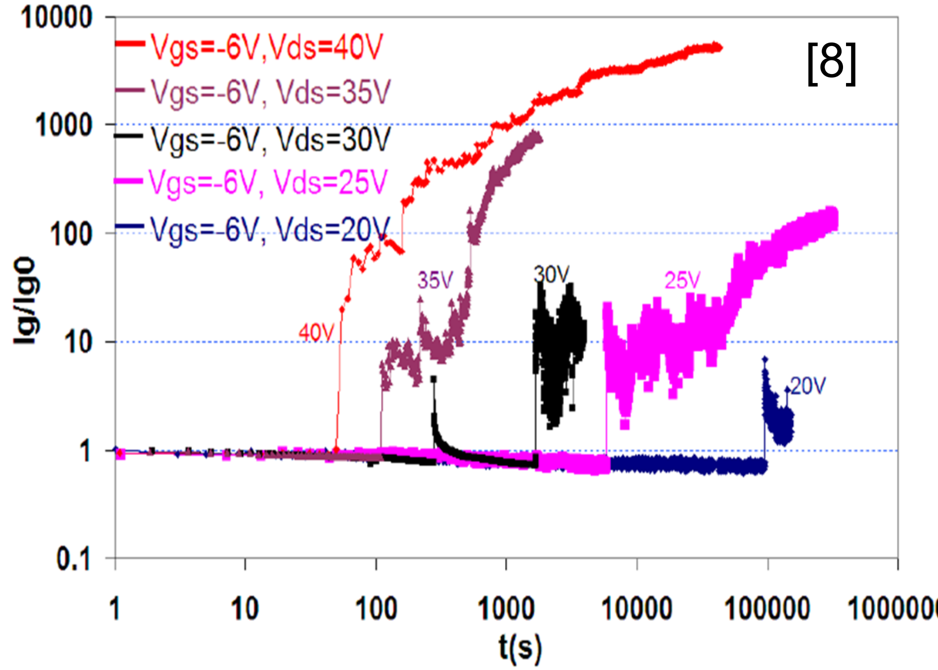




- I_G degradation at V_{crit} is time-dependent
- V_{crit} for device degradation is dependent on time step of electrical step stress

Time Dependent I_G Degradation Under CVS





- Degradation in I_G is observed at voltages below V_{crit}
- Time Dependent mechanism is contributing towards device degradation

8. D. Marcon et. al. IEDM 2010

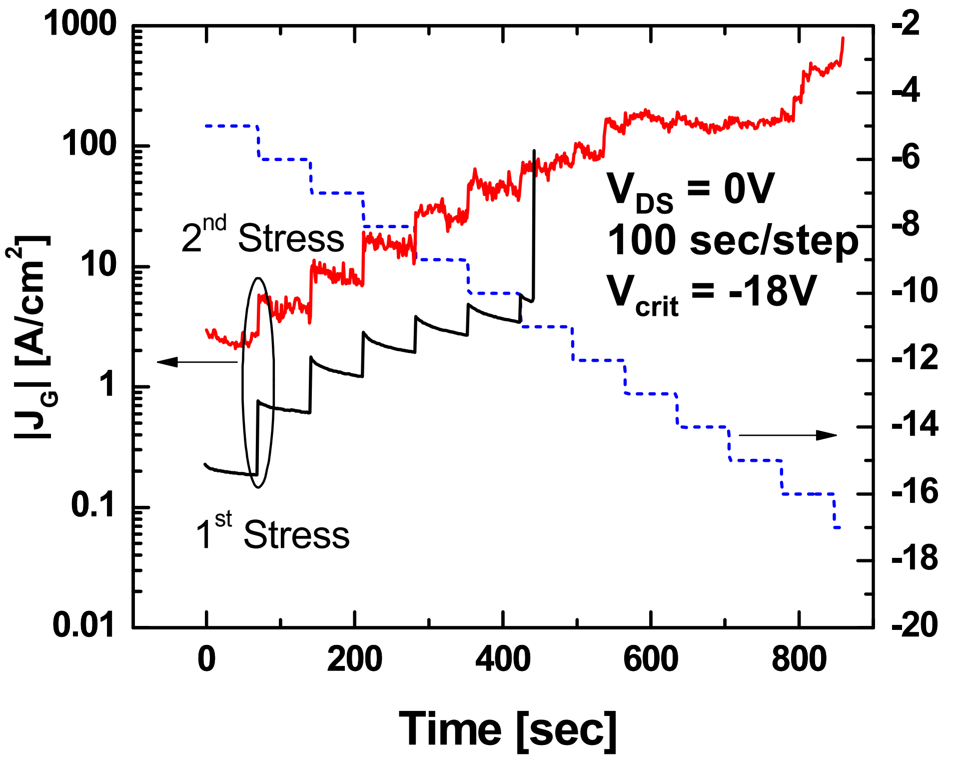
Factors Influencing Time-Dependent Mechanisms

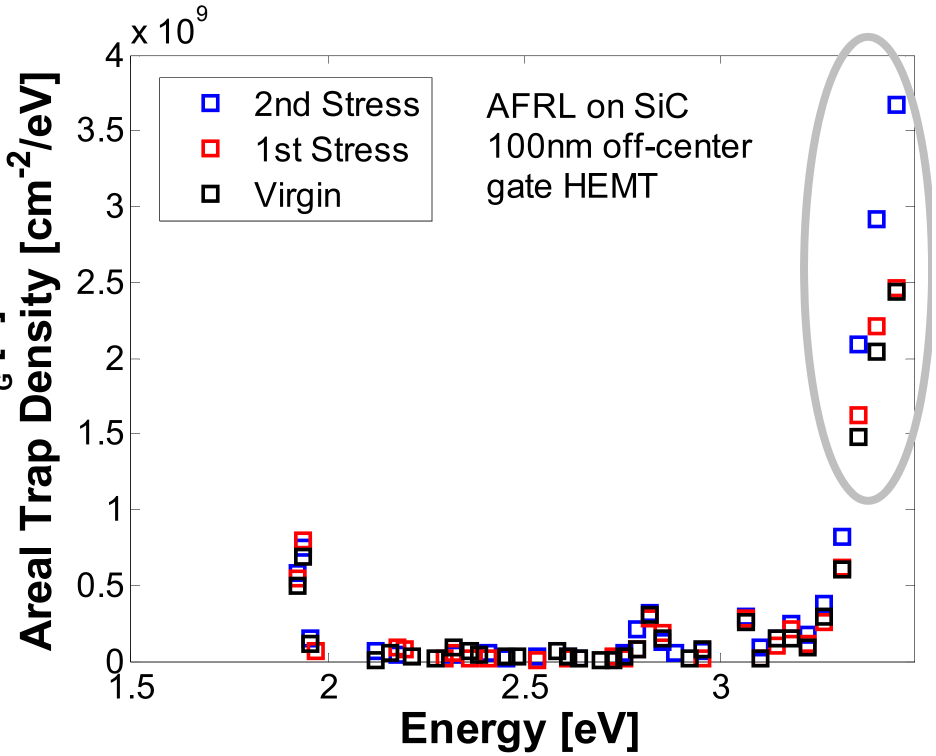
- Trap Generation [9]
  - In-built edge/threading dislocation density
  - Formation energy of traps
    - Thermal energy
    - Electrical energy
    - Mechanical energy

- Diffusion at Interface [10]
  - Concentration of diffusing material
  - Traps/defects
  - Diffusion coefficient dependent on
    - Thermal energy
    - Electrical energy
    - Mechanical energy

9. Brian W. Dodson and J. Y. Tsao, APL, 51, 26, 1987.
10. E. B. Cowern , P. C. Zalm , P. van der Sluis , D. J. Gravesteijn , and W. B. de Boer, Phys. Rev. Lett., 72, 1994

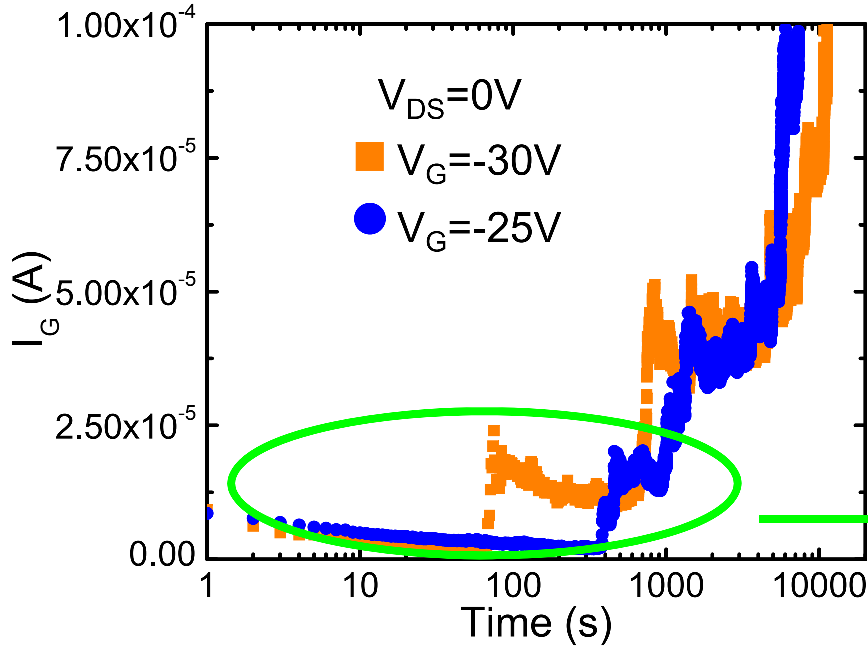
Photoionization Spectroscopy of Electrically Stressed GaN HEMT

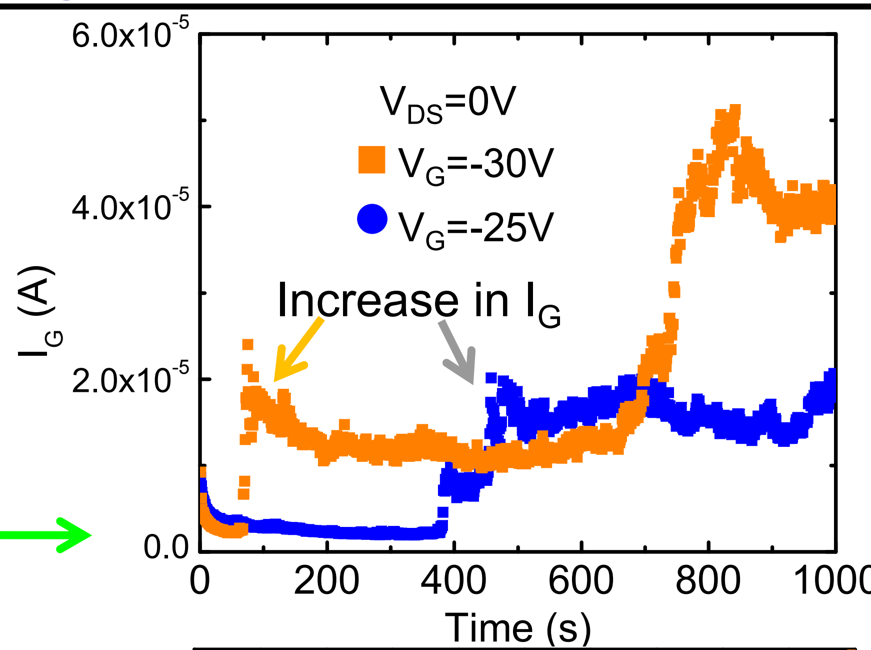


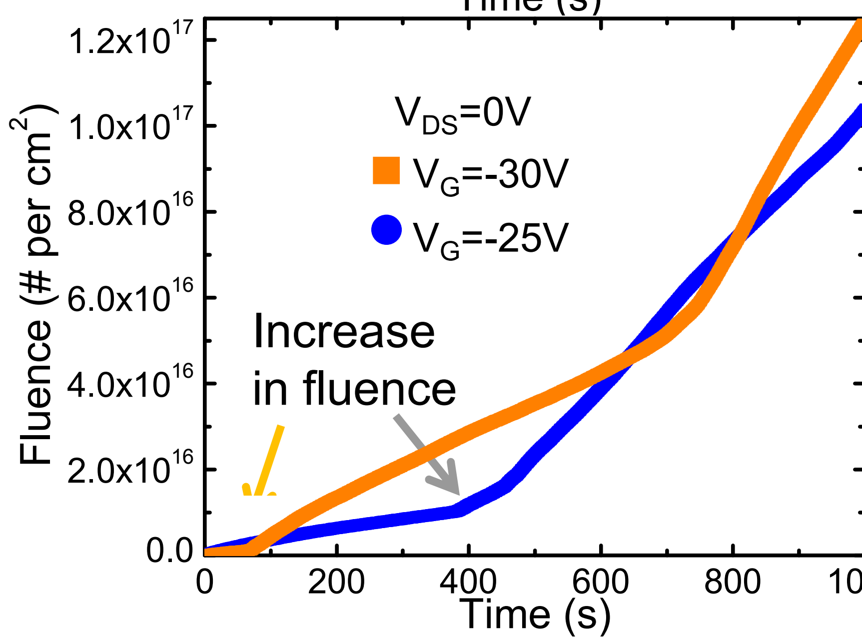


- Structural (near bandgap) defect density increases significantly with extended electrical stressing

Fluence During I_G Degradation







- Effect of gate fluence at onset of early stage I_G degradation
  - Stress, temperature, field, carrier, and impurity effect on degradation

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Strain Relaxation By Trap Generation

• GaN HEMT have high density of dislocations – screw, edge, threading [11]

• Strain relaxation in III-V material system can occur through [12,13]

- Condensation of point defects
- Dislocation growth from seed
- Dislocation half loop glide
- Edge dislocation tilt

• Increase in size of structural damages (cracks/pits) is observed in GaN HEMT upon electrical stressing [14]

11. M. Haugk et. al. ,phys. stat. sol. (b) 217, 423, 2000
12. M.E. Twigg et. al.,JAP, 101, 053509 , 2007
13. Lisa Sugiura, APL, 70, 1317,1997
14. P. Makaram, et. al., APL, 96, 233509, 2010

Kinetics Of Dislocation Multiplication

- Rate of strain relaxation, $\frac{d\varepsilon(t)}{dt}$, is related to rate of dislocation generation, $\frac{d\rho_m}{dt}$ [15].

$$\frac{d\varepsilon(t)}{dt} = b\frac{d\rho_m}{dt} \quad , \; b \rightarrow Magnitude\ \ of\ \ Burgers\ vector$$

- Rate of dislocation multiplication is dependent on dislocation motion as [16]

$$\frac{d\rho_m}{dt} \propto \rho_m \cdot v \cdot \sigma_{eff}$$

ρ_m (cm^{-3}) - Edge/misfit dislocation density

σ_{eff} (dyne.cm^{-2}) - Effective stress in epitaxial layer

(E-field, externally applied mechanical stress, thermal mismatch)

v (cm.s-1) - Dislocation glide velocity $\quad v \propto \sigma_{eff} \cdot \exp\left(-\frac{E_A}{kT}\right)$

(Thermally activated)

- Activation energy of dislocation motion (E_A) is dependent on lattice energy [17]

15. Brian W. Dodson and J. Y. Tsao, APL, 51, 26,, vol. 22, Academic, New York 1968

17. Lisa Sugiura, App. Phy. Lett., 70, 1317,19971987.

16. H. Alexander and P. Haasen, Solid State Physics

Strain Relaxation By Diffusion

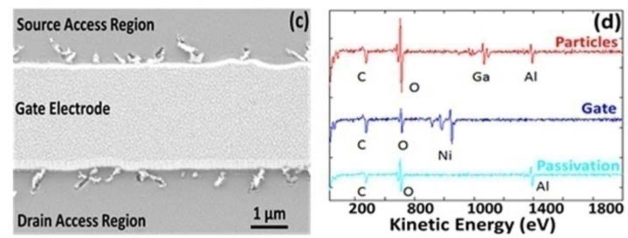
- Diffusion in a strained layer is given by [18]-

$$\hat{D} = D_{(i)} \exp\left(\frac{-Q'_{(i)}\varepsilon}{kT}\right) + D_{(v)} \exp\left(\frac{-Q'_{(v)}\varepsilon}{kT}\right)$$

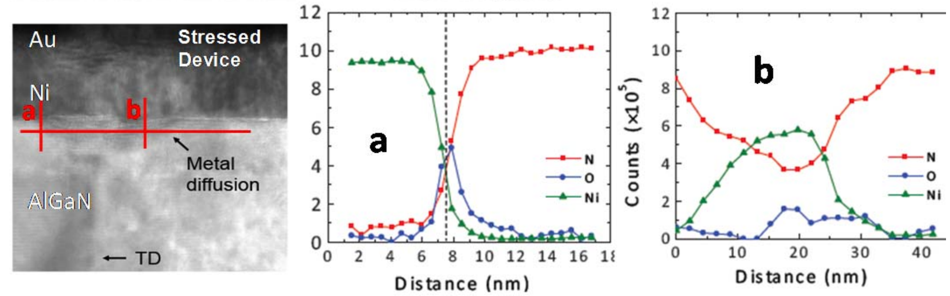
(i) – Interstitials, (v) – vacancies
k – Boltzmann constant
T – Temperature (K)
D – Diffusion coefficient under no strain ($cm^2\, s^{-1}$)
-Q' -- Activation energy per unit strain (eV)
(Thermally activated, active traps dependent)
ε -- Strain in epitaxial Layer

(E-field, externally applied mechanical stress, thermal mismatch)

- GaN HEMT device degradation due to diffusion in the AlGaN layer has been reported
  - Oxygen diffusion [19]



  - Gate metal (Ni) diffusion [20]



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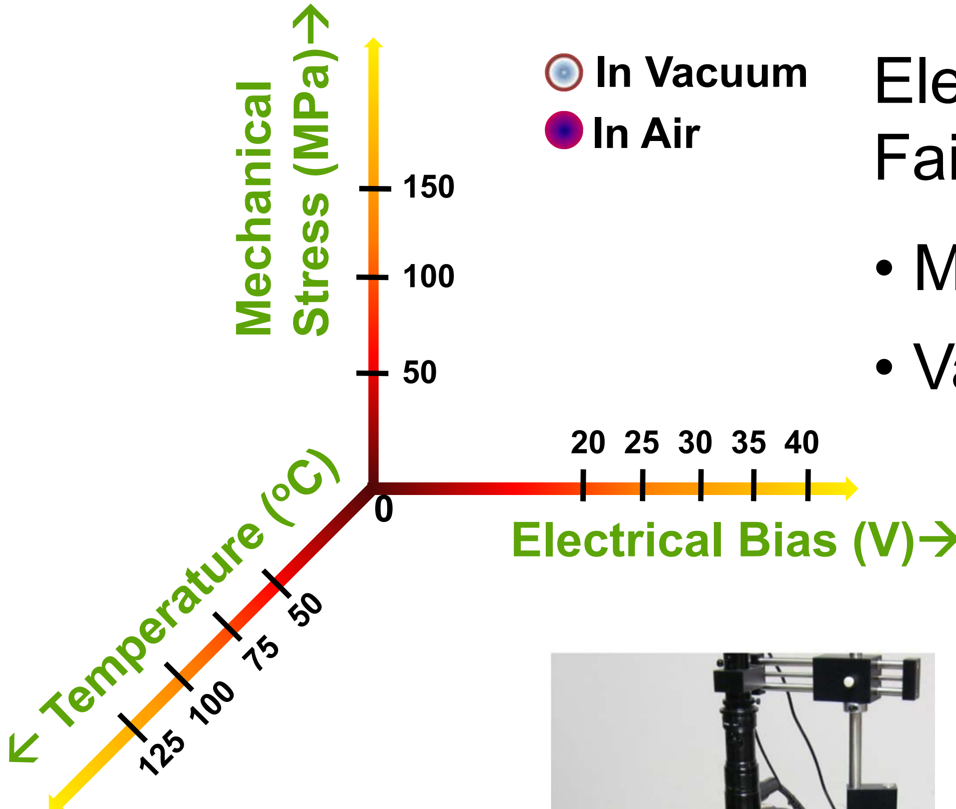
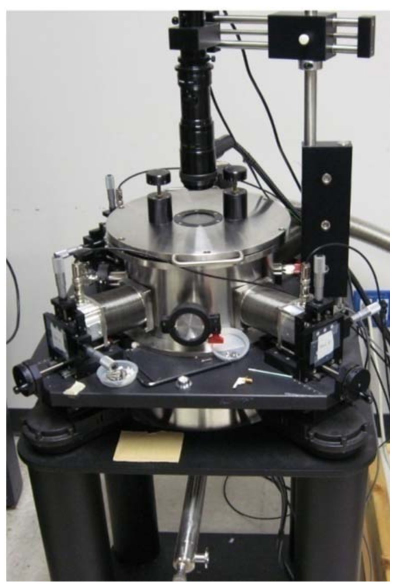
19. Feng Gao et. al., Appl. Phys. Lett. 99, 223506, 2011
20. L. Liu, et al., J. Vac. Sci. Technol. B 29, 032204, 2011

Stress, Temperature, Field, Carrier Study



Electrical Characterization Of Device Failure

- Monitor I_G degradation at V_{DS}=0V
- Vary measurement conditions:
  - ▪Mechanical stress
  - ▪Temperature
  - ▪Electrical bias (reverse V_G)
  - ▪Oxygen content *(in Vacuum / Air)*



Lakeshore vacuum probe station (77K to 400K)

Custom 4-point uniaxial wafer bending setup

Outline

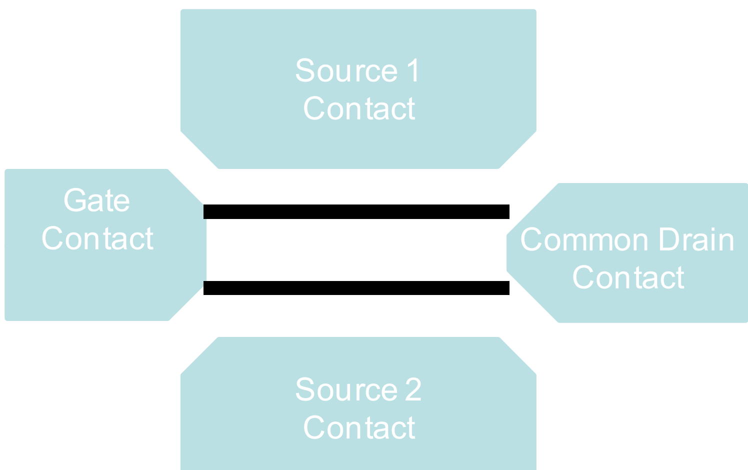
- Motivation
- Gate Leakage Stress Dependence in AlGaN/GaN Schottky Diode
- Photoionization Spectroscopy – Trap Characterization
- Understanding Degradation Mechanisms in GaN HEMT
- Design of AlGaN/GaN HEMT Test Structures and Layout
- Summary and Future Work

Design of RFMD/AFRL Test Structures

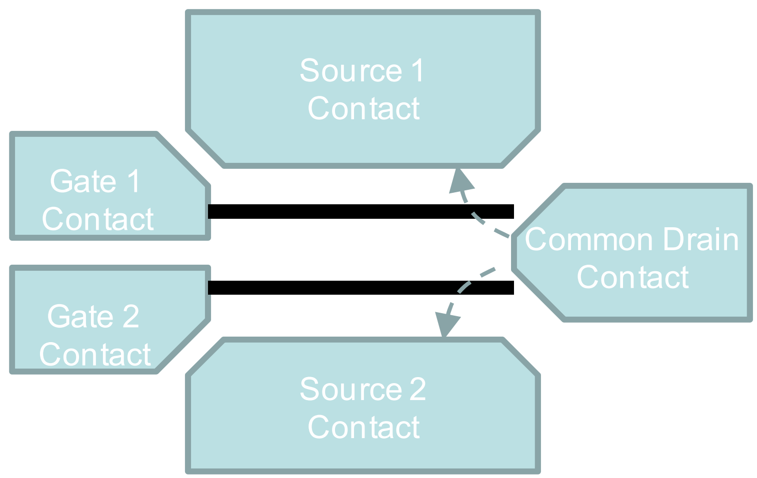
- AlGaN HEMT Structures
- AlGaN/GaN HEMT Kelvin Structures
- Circular Gate Schottky Diodes
- Square Gate Schottky Diodes
- Sub-reticle Layout
- Reticle Layout

AlGaN/GaN Proposed Structures

2-finger Gate HEMT Structure

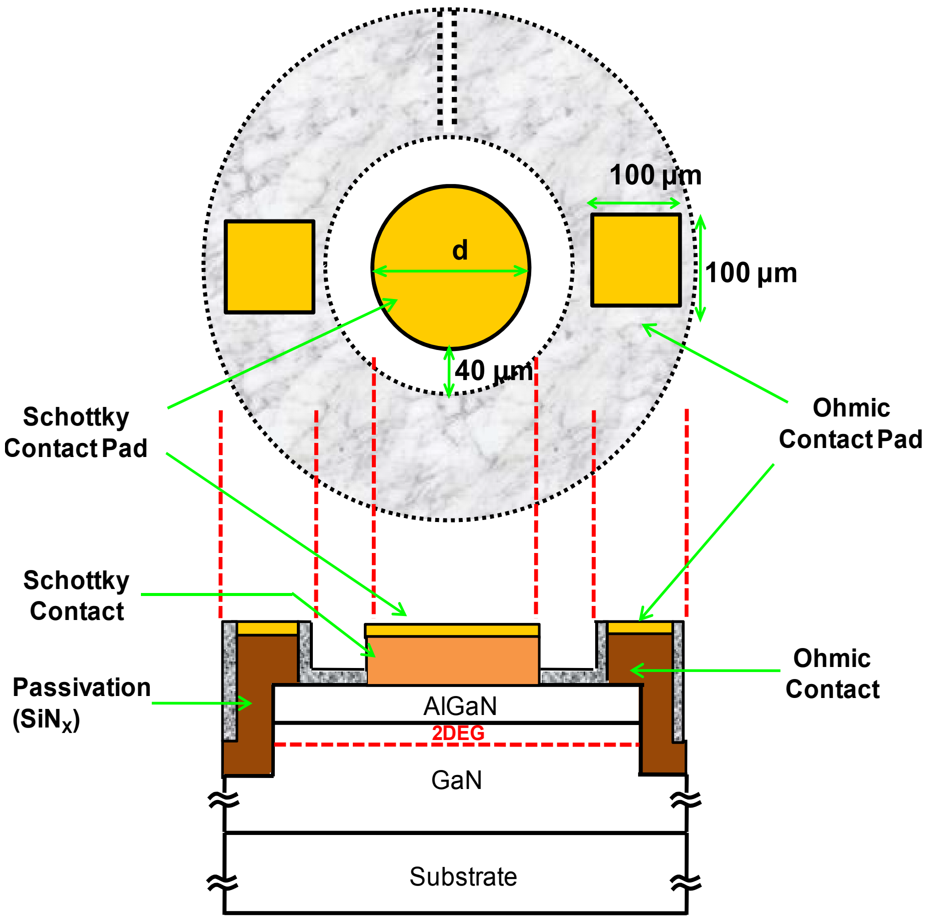


Kelvin HEMT Structure

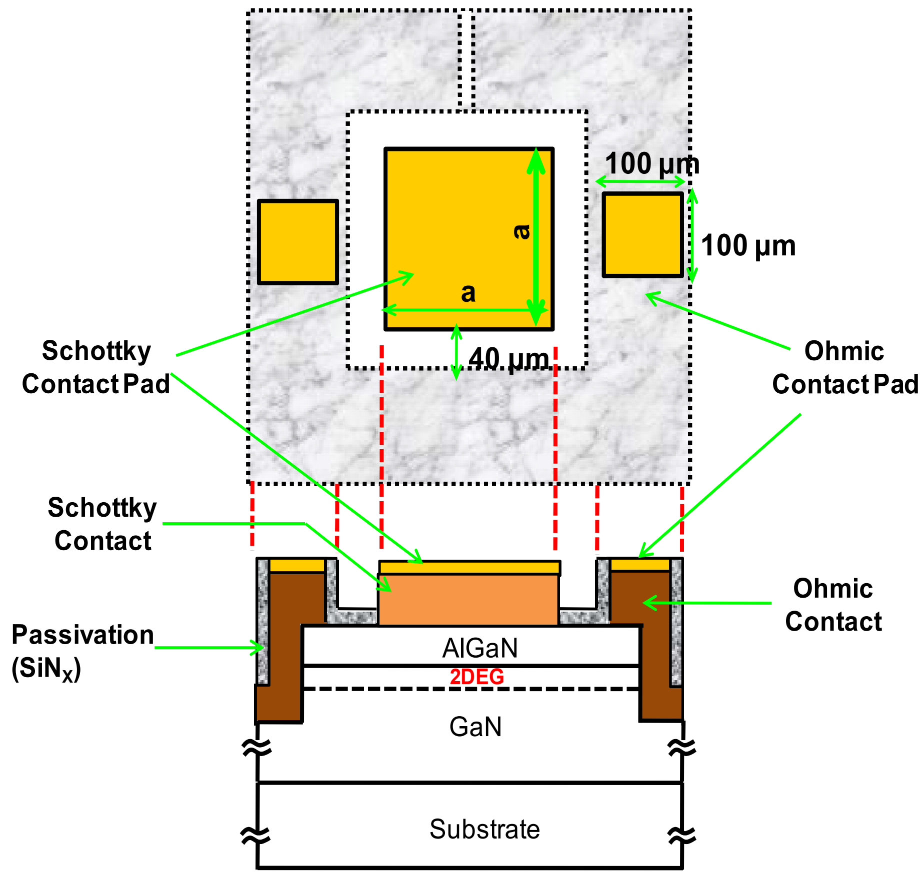


AlGaN/GaN Schottky Diodes

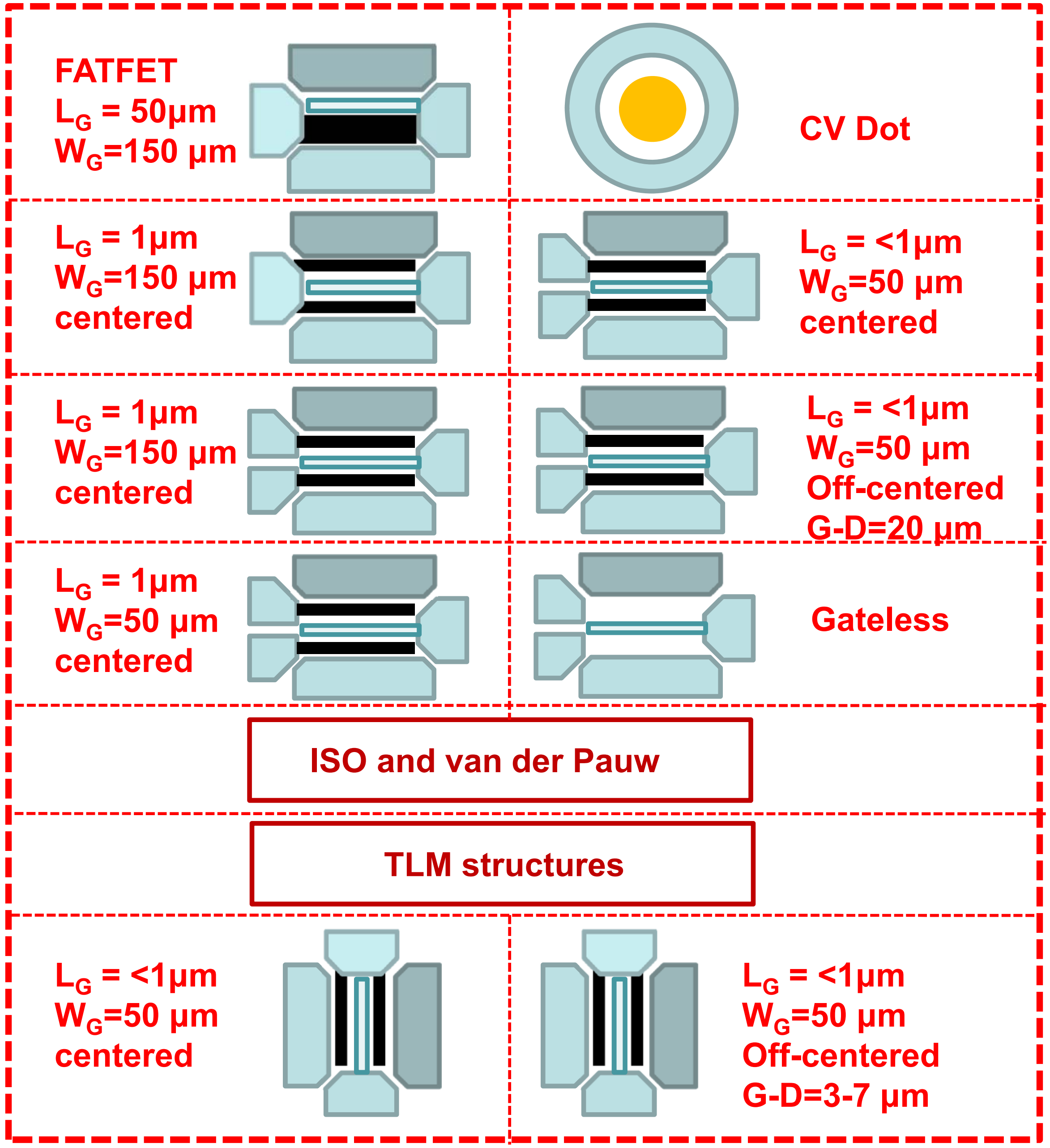
Circular Gate



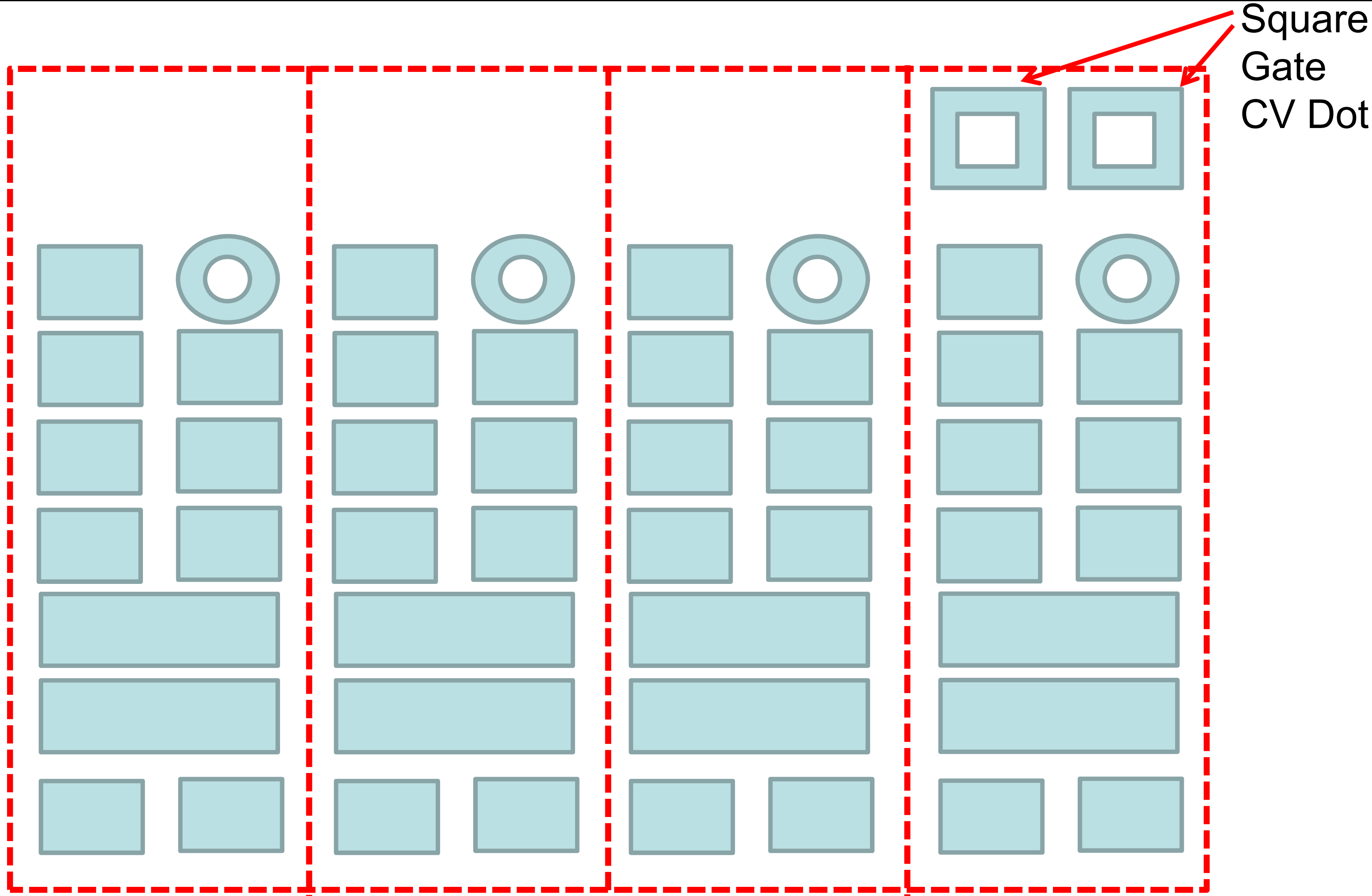
Square Gate



Proposed Sub-reticle Layout



Proposed Reticle Layout



Sub-reticle A
Sub-μ L_G=170nm
CV dot d=250μm

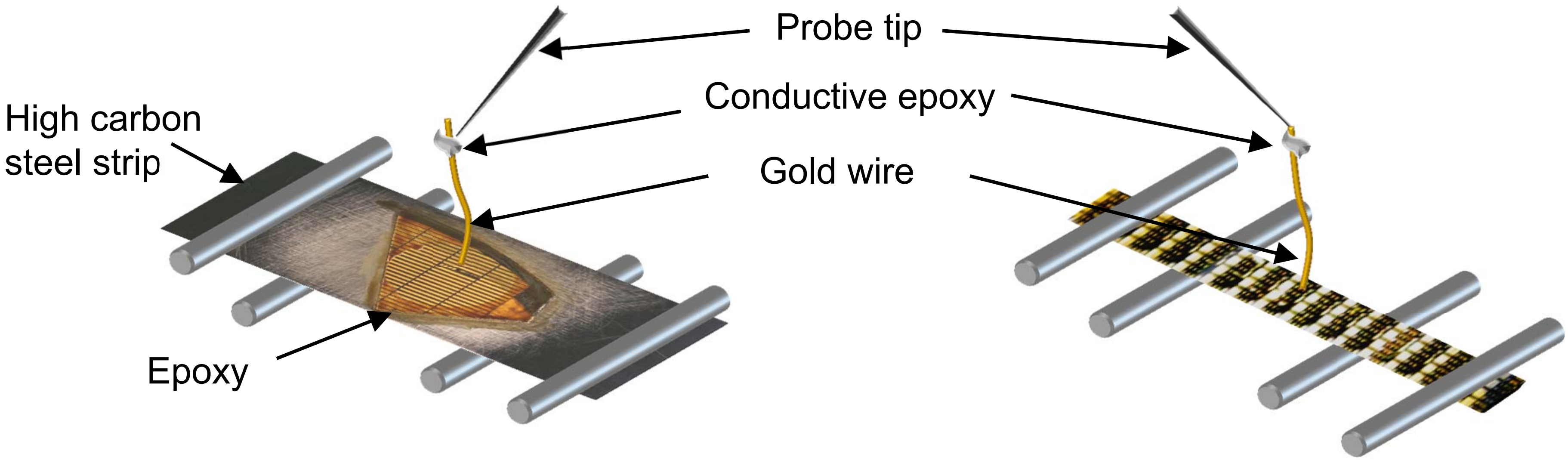
Sub-reticle B
Sub-μ L_G=140nm
CV dot d=200μm

Sub-reticle C
Sub-μ L_G=125nm
CV dot d=150μm

Sub-reticle D
Sub-μ L_G=100nm
CV dot d=100μm

Wafer Sample Size for Mechanical Bending

- Wafer strips for direct bending of 100um thick SiC substrate samples in 4-point bending apparatus
  - 0.5” x 0.15” (12.7mm X 3.8mm)



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Summary and Future Work

- Determined stress dependence of gate leakage current in a AlGaN/GaN Schottky diode structure and compared it with AlGaN/GaN HEMTs results

- Applied optical trap characterization technique using photoionization spectroscopy in AlGan/GaN HEMT

- Analyzed time dependence of early stage I_G degradation at V_{DS}=0V in AlGaN/GaN HEMTs

- Designed test structures for RFMD/AFRL AlGaN/GaN HEMT mask design

FUTURE WORK

- Investigate dependence of AlGaN/GaN HEMT degradation on mechanical stress, temperature, field, and carrier fluence

- Develop stress, temperature, field, and fluence dependent models for AlGaN/GaN HEMT degradation for integration into FLOORS

Acknowledgments

MURI FUNDING

Effect of Mechanical Stress on Gate Current and Degradation in AlGaN/GaN HEMTs

QUESTIONS?